horticulturae

MDPI

Article

Plant Density Recommendations and Plant Nutrient Status for High Tunnel Tomatoes in Virginia

Emmanuel Torres-Quezada * and Ricardo José Gandini-Taveras

Eastern Shore Agricultural Research and Extension Center, Virginia Tech, Painter, VA 23420, USA; rgandini@vt.edu
* Correspondence: etorres@vt.edu; Tel.: +1-352-682-0708

Abstract: Open-field tomatoes in Virginia are traditionally planted in a single row with 2 ft (0.60 m) of in-row spacing, resulting in a plant density of 4356 plants per acre (10,890 plants/ha). However, there has been increasing interest among small and medium-sized farmers in high tunnel production. In order to be profitable, farmers must maximize their yield per unit area and take advantage of the potential benefits of producing under high tunnels. A common approach under greenhouse conditions is to increase the planting density to enhance yield per area. However, high tunnel farmers often extrapolate open-field practices to their high tunnels as they believe both systems are closer related together than to greenhouse production. In those cases, high tunnel farmers could potentially be neglecting yield increases due to their planting density selection. Additionally, irrigation and fertilization management (fertigation) under high tunnels tend to be more efficient than open-field systems, as the frequency of application is increased with a lower volume per application. A higher efficiency of fertigation could alter plant yield responses, especially under traditional planting-density systems. Hence, this study aimed to identify the effect of high planting density on high tunnel tomatoes and their nutrient status on the Eastern Shore of Virginia. The experiment was established on a completely randomized block design with four replications, with 20 ft (6.09 m) experimental plots. We evaluated the combination of two in-row distances and single and double planting rows, with treatments consisting of 2 ft of in-row distance in a single row (4356 plants/acre—current open-field recommendation), 1.5 ft (0.45 m) of in-row distance in a single row (5808 plants/acre [14,520 plants/ha]), 2 ft of in-row distance in a double row (8712 plants/acre [21,780 plants/ha]), and 1.5 ft of in-row distance in a double row (11,616 plants/acre [29,040 plants/ha]). Summer-grown tomatoes produced on the Eastern Shore of Virginia under high tunnel conditions should be planted with 2 ft of in-row spacing and with a single row of plants per planting bed. Increasing the plant density or modifying the current recommended plant distribution could result in yield losses per plant between 32% and 46% and substantial increases in production costs compared with the traditional planting density. Throughout all treatments, tomato plants did not show deficient nutrient status. We hypothesized that irrigation water and pollination were the limiting factors that promoted a decrease in yield per plant for the high-density treatments.

Keywords: in-row spacing; plant spacing; protective structures; mid-Atlantic; *Solanum lycopersicum*

check for updates

Citation: Torres-Quezada, E.; Gandini-Taveras, R.J. Plant Density Recommendations and Plant Nutrient Status for High Tunnel Tomatoes in Virginia. *Horticulturae* **2023**, *9*, 1063. https://doi.org/10.3390/horticulturae9101063

Received: 8 August 2023
Revised: 18 September 2023
Accepted: 18 September 2023
Published: 22 September 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Virginia tomato farmers produced an average of 25 tons/acre (62,500 kg/ha), with nearly 2800 acres (1120 ha) planted across the state in 2020. The Virginia tomato market produced almost USD 25 million in 2018, with most of the fruit intended for wholesale markets and distributed across the east coast of the USA [1]. Open-field tomatoes are planted in a single row per bed, with 2 ft of in-row spacing, resulting in 4356 plants/acre [2]. However, throughout the last 10 years, there has been increasing interest in high tunnels among small and medium farmers in the Mid-Atlantic region [3]. High tunnels can help farmers extend their production season, protect plants and fruits from heavy rain,

wind, and drastic changes in temperature, and increase overall yield and quality through more efficient management of irrigation water and fertilizers [4–6]. However, to take advantage of the potential benefits of producing under a protected system and improve profitability, farmers must focus on maximizing their yield per unit area and increasing their input management efficiency [7]. In many cases, these two constraints may lead to the establishment of a specific production system for high tunnels, compared with open-field production. Nevertheless, many farmers in the USA still extrapolate some open-field production practices to high tunnels, as they see the structure as a complement to their traditional system, partially neglecting the potential yield increases related to high tunnel production.

The selection of plant density has a direct effect on yield per unit area, light interception, and efficiency of resources, as plants actively compete for space and solar radiation above ground, and for water and essential nutrients below ground, in a rhizosphere restricted by the perimeter of the planting bed. There is a direct relationship between plant density, interception of solar radiation, and biomass production [8–10]. Variations in light quality and quantity due to high-planting-density environments can trigger changes in plant photomorphogenesis. Plant-to-plant shading promotes changes in light quality, resulting in increasing far-red light and triggering hormonal changes that can result in the elongation of the stem cells of the plants being shaded [11]. Below ground, plants compete for water and nutrients in an environment delimited by the planting bed and plastic mulch. Under high tunnels, plants are restricted to the water and nutrients applied through the irrigation system, forcing farmers to adopt a strict management program to secure their expected yield. In the USA, farmers have empirically developed a hybrid system for high tunnels that combines practices from both open fields and greenhouses. Traditionally, many high tunnel farmers apply fertilizer through the irrigation system once per day, but not with every irrigation event. This is a clear improvement in efficiency from the weekly fertilizer applications commonly used in open fields, but it is not as efficient as the continuous application of fertilizer with each irrigation event commonly used in greenhouses. Additionally, many farmers detach from this approach and develop their own system which can vary from one application of fertilizer per week to daily applications. The lack of clear guidelines for high tunnels has created inconsistencies in farmers' approaches to managing their crops, leading to yield restrictions and economic losses, and has uncovered a clear need for research-based and location-specific recommendations that aim to maximize farmers' profitability.

Under greenhouse conditions, increasing the planting density in combination with a highly efficient regimen of water and fertilizer is a common approach to increase yield. Like greenhouses, high tunnels offer protection to plants against rainfall and high wind while allowing the integration of fertigation into the production system multiple times per week, which in turn could allow a higher planting density compared with open fields. Conversely, irrigation and fertilization under high tunnels are not traditionally managed to the same level of detail as within a greenhouse, and plants established at an unsustainable high density might underperform if the system is not modified accordingly. There are many recommendations for tomato planting density in open fields and under greenhouse conditions across most producing areas of the USA, ranging from 3.6 to 1.1 plants per square meter. However, there are no research-based plant-density recommendations for the mid-Atlantic U.S. for high tunnel conditions. Our hypothesis is that tomato plants under high tunnels could be planted at a higher density than in open-field systems, given the higher frequency of application of water and fertilizer. Hence, the objective of this study was to identify the effect of high planting density on tomato plant nutrient status under high tunnels on the Eastern Shore of Virginia.

2. Materials and Methods

A field experiment was established between June and October 2021 at the Eastern Shore Agricultural Research and Extension Center (Lat. 37.5845, Long. −75.8190) of Virginia Tech.

The study was established under two single-bay high tunnels, with individual dimensions of 30 ft (9.14 m) width by 45 ft (13.71 m) length (1350 ft^2 [125.41 m^2]), separated by a 30 ft (9.14 m) uncovered aisle. The structures were 6 ft (1.82 m) in height on both sides and 15 ft (4.57 m) in height on the center top, with a traditional chapel shape (Figure 1). The tunnels were covered with a translucent single-layer polyethylene plastic cover 0.1524 mm thick and no drop-down curtains on the sidewalls, front, or back. The soil at the experimental area is a Bojac sandy loam soil (thermic typic hapludults), with less than 5% organic matter. Soil samples were collected at 8 inches (20.3 cm) depth and sent to the laboratory before the establishment of the experiment. The soil presented an average pH of 6.7 and soluble salt content of 0.18 mmho/cm. Additionally, soil samples contained 10.9 ppm of nitrate-N, 3.8 ppm of ammonium-N, 169 ppm of phosphorus, 70 ppm of potassium, 44 ppm of magnesium, and 315 ppm of calcium. The soil was composed of 57% sand, 30% silt, and 13% clay, with a field capacity of 25.8% at 6 kPa and a permanent wilting point of 4.7% at 1500 kPa. The area under the tunnels was tilled twice and sprayed with glyphosate (0.75 lb/acre [1.87 kg/ha]), 3 weeks before the establishment of the experiment. Planting beds were 24 inches (61 cm) at the base, 22 inches (56 cm) at the top, and 8 inches (20.3 cm) in height, with a trapezoidal shape, and covered with a white-on-black plastic mulch, 0.0317 mm thick (Berry Hill Drip Irrigation, Buffalo Junction, VA 24529). The white surface of the mulch was placed facing toward the outside of the planting bed to maximize light reflectance and reduce the soil temperature. Additionally, during the bed preparation process, a single drip line (0.381 mm, 0.94 LPH) with emitters every 12 inches (30.48 cm) (AquaTraxx Drip Tape, Berry Hill Drip Irrigation, Buffalo Junction, VA 24529), was buried 1 inch (2.5 cm) deep into the planting bed, and approximately 1.5 (3.81 cm) inches to the right of the top center of the bed, under the plastic mulch.

Figure 1. High tunnels at the Eastern Shore Agricultural Research and Extension Center, Painter, VA, USA.

Six-week-old "Crimson Red 145307" tomato plants were transplanted under the tunnels on 12 July 2021. The experiment was established on a completely randomized block design with four replications, with 20 ft long experimental plots. Planting density treatments were defined as the combination of two in-row distances and single and double planting rows per bed, with treatments consisting of 2 ft of in-row distance in a single row (4356 plants/acre), 1.5 ft of in-row distance in a single row (5808 plants/acre), 2 ft of in-row

distance in a double row (8712 plants/acre), and 1.5 ft of in-row distance in a double row (11,616 plants/acre) (Figure 2).

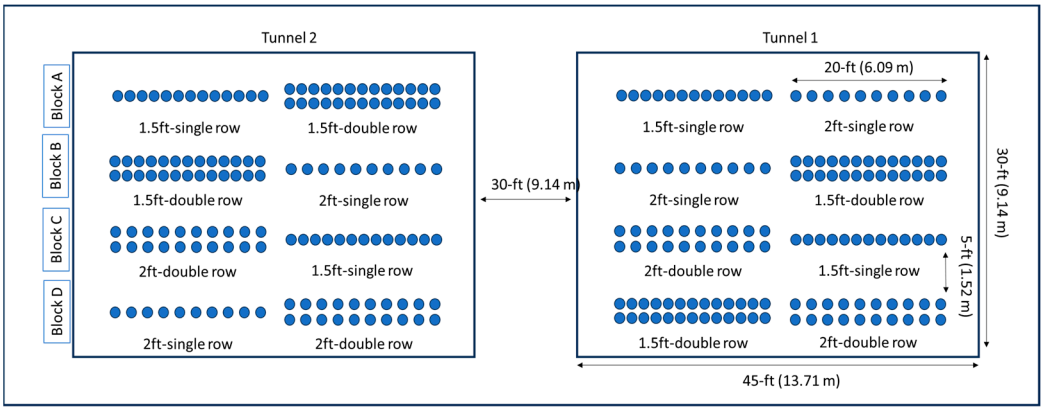

Figure 2. Treatment diagram and spatial distribution of tunnels at the Eastern Shore Agricultural Research and Extension Center, Painter, VA, USA.

Tomato plants were irrigated once per day, between 9:00 and 14:00, for a minimum of 40 min (equivalent to ≈ 1.4 mm/day). Pre-plant fertilizer was applied at 60 lb/acre of nitrogen (N), phosphate (P_2O_5), and potash (K_2O), using a dry formulation of 10-10-10 at a rate of 600 lb/acre (681 kg/ha), during the process of bed preparation. After transplanting, tomato plants were fertilized three times per week using a formulation of urea–ammonium nitrate (32%N), triple super phosphate (46% P_2O_5), and potassium chloride (60% K_2O) at a rate of 1-0.5-0.5 lb/acre (2.5-1.25-1.25 kg/ha) of N-P_2O_5-K_2O per day. The dry fertilizer for weekly injections was diluted and injected through the irrigation system using a piston injector at a rate of 1:150 (151.4 L Dosatron Fertilizer Injector, Berry Hill Drip Irrigation, Buffalo Junction, VA 24529). The combination of the pre-plant fertilizer and weekly fertilizer applications resulted in a total applied fertilizer rate per acre of 145 lb (164 kg/ha) of N, 102 lb (115.9 kg/ha) of P_2O_5, and 102 lb (115.9 kg/ha) of K_2O (throughout ≈ 3 months). All irrigation and fertilization practices were in accordance with the commercial standard for tomatoes, based on the recommendation of the *Mid-Atlantic Commercial Vegetable Production Recommendation Handbook*.

We collected daily average, maximum, and minimum air temperature data inside the high tunnel, using a Temp/RH data logger located at the center of the structure, between the tomato plants at 6 inches (15.2 cm) above the planting bed surface (MX2301A; OnSet, Bourne, MA, USA). We also collected plant height and tissue samples for foliar nutrient concentration analysis at 4, 8, and 12 weeks after transplant (WAT), using five randomly selected plants from each plot. Tissue samples were composed of five true leaves per plot, collected from the middle of the plant and avoiding apical leaves, damaged leaves, and leaves showing signs of senescence. Tissue samples were dried to a constant weight and sent to an external laboratory for concentration analysis of N, phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg). Total N was determined by oxygen combustion gas chromatography with subsequent quantification using a thermal conductivity detector. Total P, K, Ca, and Mg concentrations were determined with inductively coupled plasma–optical emission spectrometry (ICP-OES), after closed-vessel nitric acid (HNO_3) digestion in a microwave digestion system. Tomato plants were harvested four times in the season, starting at 13 WAT. A marketable fruit was defined as a tomato without visible blemishes, with a minimum diameter of 54 mm, and more than 10% but not more than 30% of the surface showing a definite change in color from green to tannish yellow, pink, red, or a combination of those colors. Fruits with visible blemishes, mechanical damage, or deformation, and/or smaller than the minimum requirement were considered unmarketable. Average fruit weight was calculated from the total marketable weight divided by the total marketable fruit number per plot. All variables were analyzed using an analysis

of variance at 5% confidence (Statistix10) for interaction and single-factor effect. In the case of identifying differences among treatment means, data were separated using Fisher's least significant difference test at 0.05%.

3. Results

Throughout our study, tomato plants were subjected to slightly above-adequate growing temperatures until 2 September 2023 (Figure 3). The recommended average air temperature for tomato production ranges between 60 °F–80 °F (15.5 °C–26.6 °C). In our case, the average daily temperature in July was 79.2 °F (26.2 °C), with average minimum and maximum daily temperatures of 70.5 °F (21.4 °C) and 88 °F (31.1 °C), respectively. Similarly, in August, the average daily air temperature was 78.6 °F (25.8 °C), with a minimum of 70.9 °F (21.6 °C) and a maximum of 86.3 °F (30.1 °C) (Figure 3). After early September, the average air temperature started to steadily decrease until the end of the study. The average daily air temperature in September was 72.1 °F (22.2 °C), with a minimum of 63.3 °F (17.4 °C) and a maximum of 81 °F (27.2 °C). The maximum, minimum, and average air temperatures throughout the study were recorded at 95 °F (35 °C), 42 °F (5.5 °C), and 74.1 °F (23.4 °C), respectively (Figure 3).

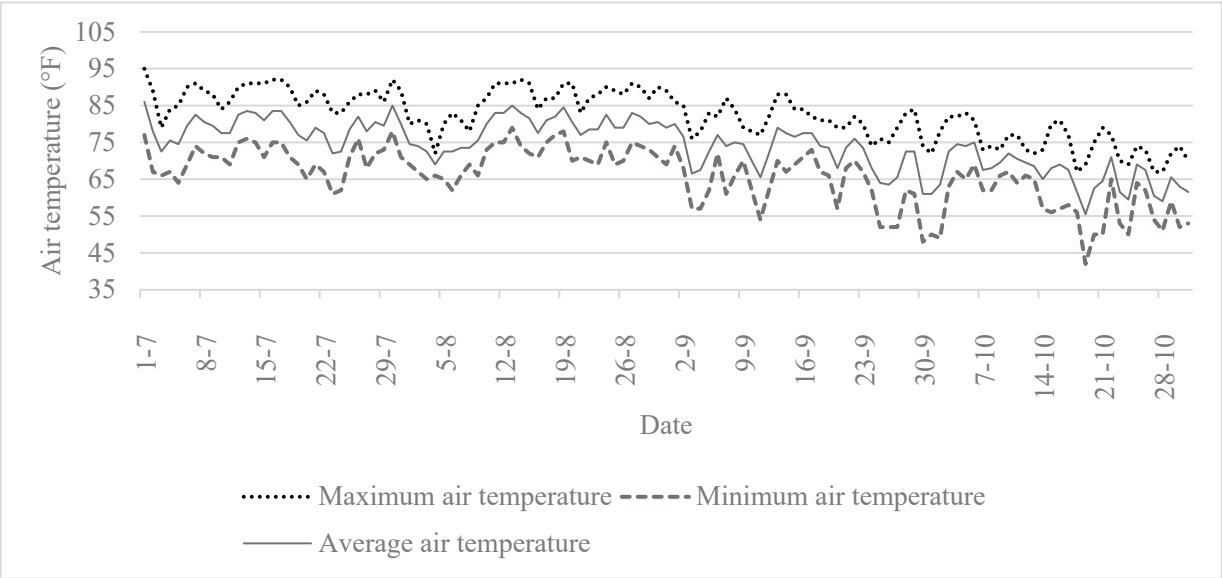

Figure 3. Average, maximum, and minimum air temperature inside the experimental high tunnel between 1 July and 31 October 2023, at Painter, VA, USA.

There was no main-factor effect nor interaction between in-row distance and the number of planting rows for plant height at 4, 8, and 12 WAT, with an average plant height of 22.5 inches (57.1 cm) at 4 WAT, 44.9 inches (114 cm) at 8 WAT, and 47.4 inches (120.4 cm) at 12 WAT (Table 1). Additionally, there was no main-factor effect nor interaction between the independent variables for marketable fruit number per plant, marketable fruit weight per plant, average fruit weight, unmarketable fruit number and weight per plant, and average unmarketable fruit weight (Table 2). Tomato plants under high tunnels produced an average of 108,882 marketable fruits per acre (272,205 fruits/ha), with an average fruit weight of 202 g, resulting in a total marketable yield of 49.2 tons/acre (123 Mg/ha) (Table 2). Additionally, plants produced 39,939 unmarketable fruits per acre (99,847 fruits/ha), with an average fruit weight of 96.3 g per fruit, producing an average unmarketable yield of 8.1 tons/acre (20.2 Mg/ha). On average, the total yield of the high tunnel system was 57.3 tons/acre (143.2 Mg/ha), with 85.8% marketable yield and 14.2% unmarketable production (Table 2).

Table 1. Effect of in-row distance and the number of planting rows on tomato plant height at 4, 8, and 12 weeks after transplanting under high tunnel production at Painter, VA, USA.

Factor	Plant Height (Inches) (1)		
In-Row Distance (IR)	**4 WAT**	**8 WAT**	**12 WAT**
1.5 ft	22.94 ± 0.69	45.22 ± 1.85	47.60 ± 1.46
2 ft	22.03 ± 0.57	45.25 ± 1.56	47.36 ± 1.79
Significance (≤ 0.05)	0.2226	0.9904	0.925
Planting rows (PR)			
1 row	23.64 ± 0.48	44.55 ± 0.93	45.88 ± 0.98
2 rows	21.32 ± 0.49	44.92 ± 2.23	49.08 ± 1.91
Significance (≤0.05)	0.0087	0.8164	0.2199
IR × PR (≤0.05)	0.9609	0.3326	0.775

(1) 1 inch = 2.54 cm; 1 ft = 30.48 cm; WAT = weeks after transplanting. Mean averages are followed by standard error values.

Table 2. Effect of in-row distance and the number of planting rows on marketable and unmarketable tomato fruit numbers and weight, and average fruit numbers per acre under high tunnel production at Painter, VA, USA.

Factor	Fruit Yield and Number per Acre					
In-Row Distance (IR)	**Marketable Fruit Number (Fruit × 1000/acre)**	**Marketable Fruit Weight (Tons/Acre) (1)**	**Average Fruit Weight (Grams/Fruit)**	**Unmarketable Fruit Number (Fruit × 1000/acre)**	**Unmarketable Fruit Weight (Tons/Acre)**	**Average Unmarketable Fruit Weight (Grams/Fruit)**
1.5 ft	104.71 ± 15.50	45.84 ± 7.20	199.2 ± 3.53	39.26 ± 11.29	8.30 ± 2.18	100.61 ± 8.42
2 ft	110.79 ± 17.41	52.52 ± 9.27	205.12 ± 7.17	40.62 ± 12.92	7.99 ± 1.95	91.98 ± 6.09
Significance (≤0.05)	0.3995	0.2973	0.3254	0.8342	0.7696	0.4376
Planting rows (PR)						
1 row	104.82 ± 17.43	46.36 ± 9.64	199.2 ± 7.29	44.71 ± 11.01	8.77 ± 1.78	92.15 ± 6.74
2 rows	115.22 ± 15.47	52.00 ± 7.00	205.12 ± 3.79	35.17 ± 11.82	7.53 ± 2.19	100.44 ± 7.93
Significance (≤0.05)	0.4089	0.3751	0.5252	0.1656	0.2658	0.4553
IR × PR (≤0.05)	0.8223	0.7073	0.444	0.534	0.2074	0.6861

(1) 1 ton/acre = 2.5 Mg/ha; 1 ft = 30.48 cm; WAT = Weeks after transplanting.

There was no interaction between the in-row spacing treatments and the number of planting rows in terms of yield per plant. However, decreasing the in-row spacing from 2 ft to 1.5 ft significantly decreased marketable fruit number and weight, with no effect on unmarketable yield (Table 3). Tomato marketable fruit number and weight per plant decreased by 32% and 35%, respectively, when planted at 1.5 ft of in-row spacing, compared with 2 ft. In-row spacing treatments did not affect unmarketable fruit number nor weight per plant, with an average of 14.3 fruits and 2.8 lb per plant (1.27 kg/plant) (Table 3). Similarly, increasing the number of tomato rows from one to two rows per planting bed decreased marketable fruit number and weight per plant by 45% and 44%, respectively. Unmarketable fruit number and weight per plant also decreased by 60% and 56% when tomatoes were planted in two rows per bed (Table 3). However, this was probably related to the overall decrease in yield as the total yield per plant was 46% lower for treatments planted in two rows per bed (13.8 lb/plant [6.2 kg/plant]), compared with one row per bed (25.6 lb/plant [11.6 kg/plant]). Tomatoes planted at 1.5 ft of in-row distance (15.8 lb/plant [7.1 kg/plant]) resulted in 33% lower yield than those planted at 2 ft of in-row distance (23.7 lb/plant [10.7 kg/plant]).

Table 3. Effect of in-row distance and the number of planting rows on tomato marketable and unmarketable fruit numbers and weight per plant under high tunnel production at Painter, VA, USA.

Factor	Fruit Yield and Number per Plant			
In-Row Distance (IR)	**Marketable Fruit Number (Fruit/Plant)**	**Marketable Fruit Weight (lb/Plant) (1)**	**Unmarketable Fruit Number (Fruit/Plant)**	**Unmarketable Fruit Weight (lb/Plant)**
1.5 ft	30.38 ± 3.96	13.19 ± 1.85	12.31 ± 2.85	2.59 ± 0.52
2 ft	45.08 ± 5.83	20.54 ± 2.65	16.41 ± 2.88	3.14 ± 0.48
Significance (≤0.05)	0.0082	0.0097	0.0926	0.1077
Planting rows (PR)				
1 row	48.77 ± 4.93	21.67 ± 2.56	20.52 ± 2.18	3.98 ± 0.30
2 rows	26.69 ± 2.35	12.06 ± 1.09	8.20 ± 1.42	1.75 ± 0.28
Significance (≤0.05)	0.0007	0.0021	0.0003	0.0000
IR × PR (≤0.05)	0.2547	0.2260	0.8132	0.2547

(1) 1 lb = 454 g; 1 ft = 30.48 cm; WAT = Weeks after transplanting. Mean averages are followed by standard error values.

Plant tissue analysis showed no main-factor nor interaction effect of in-row distance and number of planting rows on N (avg. 3.46%), P (avg. 0.28%), K (avg. 3.14%), Ca (avg. 2.71%), Mn (avg. 0.53%), and S (avg. 0.26%) tissue concentrations (Table 4). However, we did identify an effect of the sample collection date on the tissue nutrient concentration. At 4 WAT, tissue concentrations of N, P, K, Ca, Mn, and S were higher than at 8 and 12 WAT for all treatments (Table 4). Nitrogen and K tissue concentrations decreased by 42% and 46%, respectively, from 4 WAT to 12 WAT, across all treatments. Phosphorus, Ca, and Mn concentrations decreased at 8 WAT, compared with 4 WAT. However, concentrations stayed stable through 12 WAT (Table 4). Sulfur concentration decreased by 20% at 8 WAT sampling compared with 4 WAT. However, concentrations came back up at 12 WAT sampling compared with 8 WAT (Table 4).

Table 4. Effect of in-row distance and number of planting rows on tomato nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur tissue concentrations under high tunnel production at 4, 8, and 12 weeks after transplanting at Painter, VA, USA.

Factor	Tissue Nutrient Concentration (%)					
In-Row Distance (IR)	**Nitrogen**	**Phosphorus**	**Potassium**	**Calcium**	**Magnesium**	**Sulfur**
1.5 ft	3.42 ± 0.17	0.28 ± 0.22	3.89 ± 0.22	2.64 ± 0.12	0.52 ± 0.03	0.26 ± 0.01
2 ft	3.50 ± 0.19	0.28 ± 0.02	3.89 ± 0.26	2.79 ± 0.06	0.54 ± 0.02	0.26 ± 0.01
Significance (≤0.05)	0.3717	0.9833	0.9666	0.2476	0.3281	0.9759
Planting rows (PR)						
1 row	3.49 ± 0.19	0.28 ± 0.02	0.95 ± 0.26	2.70 ± 0.07	0.54 ± 0.02	0.27 ± 0.01
2 rows	3.43 ± 0.19	0.28 ± 0.01	3.83 ± 0.22	2.73 ± 0.12	0.53 ± 0.02	0.26 ± 0.01
Significance (≤0.05)	0.4645	0.9498	0.3267	0.7800	0.9064	0.7856
Sampling date (SD)						
4 WAT	4.64 ± 0.06 A	0.41 ± 0.02 A	5.45 ± 0.11 A	3.01 ± 0.14 A	0.69 ± 0.02 A	0.30 ± 0.14 A
8 WAT	3.06 ± 0.07 B	0.23 ± 0.01 B	3.28 ± 0.10 B	2.48 ± 0.11 B	0.47 ± 0.01 B	0.24 ± 0.11 C
12 WAT	2.68 ± 0.10 C	0.21 ± 0.01 B	2.95 ± 0.10 C	2.65 ± 0.05 B	0.44 ± 0.01 B	0.25 ± 0.05 B
Significance (≤0.05)	0.0000	0.0000	0.0000	0.0035	0.0000	0.0033
IR × RN	0.0576	0.6905	0.7120	0.4654	0.2190	0.2677
RN × SD	0.7885	0.2366	0.0953	0.0478	0.4005	0.1338
SD × IR	0.4908	0.7970	0.2902	0.0310	0.2448	0.0493
IR × RN × SD	0.8659	0.9915	0.8941	0.2504	0.0851	0.2727

WAT = weeks after transplanting; values followed by the different letters indicate that the means of cultivars are significantly different ($p \leq 0.05$) according to Fisher's protected least significant difference test; Mean averages are followed by standard error values. Means for sampling dates represent the average across all treatments for each sampling date. Values for interactions among factors represent nonsignificant or significant p-values at $p \leq 0.05$.

There was an interaction between in-row distance and sampling date for Ca and S concentrations. Treatments with an in-row spacing of 2 ft resulted in the highest S concentration in tissue at 4 WAT (0.32%). There was no difference among treatments with in-row spacing of 1.5 ft at 4 (0.27%), 8 (0.26%), and 12 WAT (0.26%), and 2 ft of in-row spacing at 12 WAT (0.25%). In-row spacing of 2 ft at 8 WAT (0.22%) resulted in the lowest S tissue concentration. Similarly, there was an interaction between the number of planting rows and the sampling date, and in-row spacing and sampling date for Ca tissue concentration. In-row spacing of 2 ft at 4 WAT resulted in the highest Ca concentration in tissue with 3.3%, while there was no difference among the rest of the treatments, with an average of 2.6%. Tomato treatments planted at double rows and sampled at 4 WAT resulted in the highest Ca concentration in tissue with 3.2%, followed by the single row treatment at 4 WAT with 2.8%. There was no difference among the rest of the treatments, with an average of 2.6% of Ca in tissue.

4. Discussion

Data indicate a detrimental effect in yield per plant when the tomato plant population increased outside the traditional recommendation of 2 ft of in-row spacing with plants in a single row. Yield losses ranged between 32% and 46% when the total population of plants increased from 4356 plants per acre to any of the plant densities evaluated in this study (5808, 8712, or 11,616 plant/acre), either through decreasing the in-row distance between plants or increasing the number of planting rows. Increasing the density of tomato plants compared with the traditional recommendation is likely to create an environment of competition among plants for basic resources. However, our data suggest that there was minimal competition for solar radiation and fertilizer. A common indicator of plant-to-plant shading or competition for solar radiation is the increase in plant height. Etiolation in plants is a process of morphological changes that occur when a plant is grown in low light or far-red light conditions. In optimal conditions, plants develop sturdy stems and leaves to support their overall growth and reproduction. Etiolation is a specific growth response of plants to low light conditions. Plants grown in low light or complete darkness, undergo certain morphological changes to increase their chances of capturing available light. Etiolation is characterized by increased internode length, leading to taller and spindly stems as the plant reaches for available light, as well as reduced leaf expansion and apical dominance. At the molecular level, the plant's response to low light is mediated by a complex signaling network that involves the interaction of several hormones, including auxins and gibberellins [12,13]. The accumulation of auxins in the plant's stem promotes cell elongation, leading to the characteristic tall and spindly appearance of etiolated plants [14–16]. At the same time, gibberellins stimulate the production of enzymes that break down cell walls, further promoting stem elongation. Red and far-red light play a role in regulating plant etiolation.

Far-red light conditions, detected by phytochromes, trigger a shade-avoidance response in plants. This response includes elongation growth, enhanced apical dominance, and changes in leaf morphology, collectively leading to etiolation. Under normal light conditions, phytochromes are in a state where they are more sensitive to red light than to far-red light. This means that when a plant receives sufficient red light, the phytochromes signal to the plant that there is enough light available, and the plant grows normally. However, if a plant receives more far-red light than red light, a common condition of plant-to-plant shading, or if it receives very low levels of both red and far-red light, the phytochromes will signal to the plant that light is limited, and the plant will undergo etiolation [14–16].

In our study, there was no indication of tomato plants undergoing etiolation, given that all treatments resulted in similar plant height, regardless of the moment of data collection. Moreover, the annual average solar radiation on the Eastern Shore of Virginia ranges from 4.0 to 4.5 kWh/m^2/day, which is generally considered adequate for tomato production, supporting the premise that solar radiation was not a defining factor for yield losses.

Similarly, tissue sample analysis at multiple periods during the study showed that nutrient concentration inside the plants was not affected by the planting density treatments. All values of N, P, K, Ca, Mn, and S were above the accepted adequate average levels for tomatoes of 2.5%, 0.2%, 2.5%, 1%, 0.3%, and 0.3%, respectively [17,18], suggesting that the selected fertilization program (rate, placement, source, and frequency of application) for the study supplied the required nutrients in a timely manner, without affecting growth and yield parameters. Additionally, the soil analysis at the experimental site was considered low in N, K, Ca, and Mg, supporting the hypothesis that the crop consumed most of the nutrients provided throughout the fertilization program and was not overfertilized.

Our assessment suggests that the source of the reduction in yield per plant could have been related to water availability near the root zone. Water plays a critical role in the processes of flowering and fruit production. Photosynthesis can be inhibited by a reduction in water availability, which can lead to poor growth, reduced flowering, and lower fruit production. In addition, fruit cells require sufficient water for expansion, maintenance of turgor pressure and hormone balance, and nutrient uptake. Sufficient irrigation water helps maintain turgor pressure within the fruit cell, which in turn helps to preserve the structural integrity of the cell and prevent collapsing or shrinking [19,20]. Additionally, water stress can affect the regulation of plant hormones, including the production of abscisic acid, which can inhibit fruit growth and development, resulting in smaller fruit. It is plausible that available water near the root zone provided by the irrigation system combined with the restriction of rainfall under the high tunnel, constrained plant development within the high-density treatments.

Alternately, high planting densities could have limited the ability of plants to correctly pollinate. Tomato plants are typically self-pollinating plants, with both male and female reproductive structures that often achieve pollination with minimal interference from external pollinators like insects or wind. Tomatoes can also benefit from vibration-producing bee species and wind-induced movement of the flower cluster to elicit full pollen release. Cooley and Vellejo-Marin (2021) [21] showed that both supplemental pollination by buzz-pollinating bees and open pollination by assemblages of bees, including buzz pollinators, significantly increased tomato fruit weight compared with a no-pollination control. Correct pollination is a key factor related to seed production and size, which in turn are highly correlated to fruit weight [22–24]. Under greenhouse conditions, it is common for farmers to introduce pollinators to the structure to maximize the potential yield of their system. However, it is plausible that the high-density treatments in our study limited the reach of natural pollinators to the flower clusters, as flowers could have been produced within the dense foliage of the treatment, resulting in a reduced yield per plant.

The concept of high-density planting under protective structures is not new, as most recommendations for tomato planting densities under greenhouse conditions average 3.6 plants per square meter for plants with indeterminate growth habits [25–30], compared with 1.1 plants for open-field plants with a determinate growth habit [31–33]. However, these systems are characterized by a high frequency of application of water and fertilizer, and specialized pruning activities which are not yet a common practice for high tunnels. Greenhouse recommendations have not been traditionally applied to high tunnel conditions, as it is a common belief among farmers and agricultural professionals that high tunnels closer resemble open-field conditions rather than other protective or controlled structure systems. Nevertheless, farming under high tunnels requires a higher initial investment than open-field conditions and provides partial protection to the plants, allowing better control of fertilizer and water applications, application of pruning and training practices, and installation of trellising systems. Hence, it is necessary to develop a specific production system for high tunnels designed to maximize the potential profitability for the farmer.

Similar work has been conducted in different locations around the globe, with results varying with the locations, cultivars, and confounding factors under evaluation. Zahid et al. (2020) [34] evaluated in-row spacings of 45, 60, and 75 cm in a single row in combination

with two irrigation regimens [standard and deficit irrigation] for tomatoes under high tunnels in Rachna Doab, Pakistan. Their data indicated that the highest yield per unit area was obtained with 45 cm of in-row spacing (equivalent to 1.5 ft), with no interaction with the irrigation regimen. The authors hypothesized that low levels of potassium in the soil lead to a reduction in yield in the high-density treatments. Reid et al. (2023) [35] evaluated grafted tomatoes under high tunnels in three in-row spacings in single rows [40, 50, and 60 cm]. Tomato plants produced the highest yield at 60 (equivalent to 2 ft) and 50 cm (equivalent to 1.64 ft), compared with 40 cm, while grafted tomatoes overperformed compared with non-grafted ones. Wells (1994) [36] compared in-row spacings of 30 cm, 45 cm, and 60 cm, with 1 m between planting rows, in combination with different levels of removal of side shoots. They identified that the highest yield per area was at 12 inches (equivalent to 1 ft) with no side shots, while the lowest yield per area was at 24 inches (2ft) and one side shot. Another study in Turkey evaluated 15 cm, 25 cm, and 35 cm of in-row distance in a single row in combination with different treatments of truss pruning (3, 4, 5, and 6 trusses per plant). The authors found that 35 cm (equivalent to 1.14 ft) of in-row distance produced more fruits per plant and heavier individual fruit weight than the rest of the treatments, although yield per unit area was increased with the closer spacing [37]. Conversely, Rashid et al. (2016) [38] investigated the interaction between three in-row spacings [60, 90, and 120 cm] and four N rates [0, 60, 100, 140 kg/ha] for tomatoes under high tunnels. Their research concluded that tomato plants under high tunnels produced the highest yield with a combination of 90 cm (equivalent to 2.95 ft) of in-row spacing and 100 kg/ha of N. Overall, the variation across results in the literature suggests that in-row spacing recommendations should not be generalized across production regions and systems, but rather, should be based on locally generated research data.

The objectives of our study were to identify planting density recommendations for tomatoes under high tunnel conditions for the mid-Atlantic USA and to evaluate their influence on plant nutrient status. Our results demonstrated that farmers should not seek to increase tomato plant density in high tunnels under their current production system in Virginia, as it will not result in increased yield per area. Furthermore, a simple economic estimation of the cost of implementation of high densities suggests that increasing the plant density from the standard recommendation of 4256 to 11,616 plants per acre requires an additional investment of approximately $5971 per acre ($14,927 per hectare) when considering seeds, trays, and stakes for trellising. This estimation does not account for the additional labor cost required for transplanting and maintenance of the plants. Future research should focus on the further identification of the current limitations and their potential interactions in the traditional high tunnel system and the required corresponding adjustments to maximize farmers' profits, as well as the integration of a holistic analysis during the reevaluation of the traditional production practices.

5. Conclusions

Summer-grown tomatoes produced on the Eastern Shore of Virginia should be planted with 2 ft of in-row spacing, and with a single row of plants per planting bed. Increasing the plant density or altering this plant distribution could result in yield losses between 32% and 46% compared with the traditional planting density. Tomato plants under the evaluated conditions did not seem to be competing for solar radiation or nutrient availability at our location.

Author Contributions: Conceptualization, E.T.-Q.; methodology, E.T.-Q. and R.J.G.-T.; validation R.J.G.-T.; formal analysis, E.T.-Q.; investigation, E.T.-Q.; resources, E.T.-Q.; data curation, R.J.G.-T.; writing—original draft preparation, E.T.-Q.; writing—review and editing, E.T.-Q.; visualization, E.T.-Q. and R.J.G.-T.; supervision, E.T.-Q.; project administration, E.T.-Q.; funding acquisition, E.T.-Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded internally by Virginia Tech.

Data Availability Statement: The data presented in this study are openly available in Virginia Tech Data Repository at https://doi.org/10.7294/24164079.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Virginia Department of Agriculture and Consumer Services. Virginia Agricultural Statistics 2019 Annual Bulletin. 2020. Available online: https://www.nass.usda.gov/Statistics_by_State/Virginia/Publications/Annual_Statistical_Bulletin/Annual%20Bulletin_19.pdf (accessed on 15 June 2023).
2. Torres-Quezada, E. Protective Agriculture Production Series: Plant Density Recommendations. VCE Publications/SPES/spes-474. 2022. Available online: https://www.pubs.ext.vt.edu/content/pubs_ext_vt_edu/en/SPES/spes-474/spes-474.html (accessed on 15 June 2023).
3. Vegetable Growers News. High Tunnels Use Grows in Mid-Atlantic Region. 2019. Available online: https://teams.microsoft.com/l/message/19:8f4f38cb-7c29-41f5-b07d-503d0c092cc6_b4bed328-507f-49e7-8194-5f7d7c3ab4f6@unq.gbl.spaces/1695354366599?context=%7B%22contextType%22%3A%22chat%22%7D (accessed on 15 June 2023).
4. Carey, E.E.; Jett, L.; Lamont, W.J., Jr.; Nennich, T.T.; Orzolek, M.D.; Williams, K.A. Horticultural Crop Production in High Tunnels in the United States: A Snapshot. *HortTechnology* **2009**, *19*, 37–43. [CrossRef]
5. Bruce, A.B.; Maynard, E.T.; Farmer, J.R. Farmers' Perspectives on Challenges and Opportunities Associated with Using High Tunnels for Specialty Crops. *HortTechnology* **2019**, *29*, 290–299. [CrossRef]
6. Hunter, B.; Drost, D.; Black, B.; Ward, R. Improving Growth and Productivity of Early-season High tunnel Tomatoes with Targeted Temperature Additions. *HortSci. Horts* **2012**, *47*, 733–740. [CrossRef]
7. Torres-Quezada, E.; Zotarelli, L.; Treadwell, D.D.; Santos, B.M. Growth habit and in-row distance for bell pepper under protected culture. *Int. J. Veg. Sci.* **2021**, *27*, 561–573. [CrossRef]
8. Black, C.A. *Soil-Plant Relationships*, 1st ed.; John Wiley Sons: New York, NY, USA, 1957.
9. Francis, R.; Decoteau, D.R. Developing an effective southern pea and sweet corn intercrop system. *HortTechnology* **1993**, *3*, 178–184. [CrossRef]
10. Wilson, S.D.; Tilman, D. Plant competition and resource availability in response to disturbance and fertilization. *Ecology* **1993**, *74*, 599–611. [CrossRef]
11. Wang, X.; Wang, Q.; Nguyen, P.; Lin, C. Chapter Seven-Cryptochrome-Mediated Light Responses in Plants. In *The Enzimes*; Machida, Y., Lin, C., Tamanoi, F., Eds.; Academic Press: Cambridge, MA, USA, 2014; Volume 35, pp. 167–189. ISBN 9780128019221.
12. Fitter, A.; Hay, R. Energy and Carbon. In *Environmental Physiology of Plants*, 3rd ed.; Academic Press: Cambridge, MA, USA, 2002; pp. 23–73. ISBN 9780122577666.
13. Park, Y.; Gomez, C.; Runkle, E.S. Indoor Production of Ornamental Seedlings, Vegetable Transplants, and Microgreens. In *Plant Factory Basics, Applications and Advances*; Kozai, T., Niu, G., Masabni, J., Eds.; Academic Press: Cambridge, MA, USA, 2022; ISBN 978-0-323-85152-7. [CrossRef]
14. Castro-Camba, R.; Sánchez, C.; Vidal, N.; Vielba, J.M. Interactions of Gibberellins with Phytohormones and Their Role in Stress Responses. *Horticulturae* **2022**, *8*, 241. [CrossRef]
15. Majda, M.; Robert, S. The Role of Auxin in Cell Wall Expansion. *Int. J. Mol. Sci.* **2018**, *19*, 951. [CrossRef]
16. Saidi, A.; Hajibarat, Z. Phytohormones: Plant switchers in developmental and growth stages in potato. *J. Genet. Eng. Biotechnol.* **2021**, *19*, 89. [CrossRef]
17. Hochmuth, G.J.; Hanlon, E. *Plant Tissue Analysis and Interpretation for Vegetable Crops in Florida*; University of Florida—IFAS: Gainesville, FL, USA, 2022; #HS964. Available online: https://edis.ifas.ufl.edu/publication/EP081 (accessed on 3 July 2023).
18. Souri, M.K.; Dehnavard, S. Tomato Plant Growth, Leaf Nutrient Concentrations and Fruit Quality under Nitrogen Foliar Applications. *Adv. Hortic. Sci.* **2018**, *32*, 41–48.
19. Beauzamy, L.; Nakayama, N.; Boudaoud, A. Flowers under pressure: Ins and outs of turgor regulation in development. *Ann. Bot.* **2014**, *114*, 1517–1533. [CrossRef]
20. Yang, X.; Lu, M.; Wang, Y.; Wang, Y.; Liu, Z.; Chen, S. Response Mechanism of Plants to Drought Stress. *Horticulturae* **2021**, *7*, 50. [CrossRef]
21. Cooley, H.; Vallejo-Marin, M. Buzz-Pollinated Crops: A Global Review and Meta-analysis of the Effects of Supplemental Bee Pollination in Tomato. *J. Econ. Entomol.* **2021**, *114*, 505–519. [CrossRef]
22. Varga, A.; Bruinsma, J. Roles of Seeds and Auxins in Tomato Fruit Growth. *Z. Pflanzenphysiol.* **1976**, *80*, 95–104. [CrossRef]
23. Dingley, A.; Anwar, S.; Kristiansen, P.; Warwick, N.W.M.; Wang, C.-H.; Sindel, B.M.; Cazzonelli, C.I. Precision Pollination Strategies for Advancing Horticultural Tomato Crop Production. *Agronomy* **2022**, *12*, 518–548. [CrossRef]
24. Bertin, N. Analysis of the tomato fruit growth response to temperature and plant fruit load in relation to cell devision, cell expansion and DNA endoreduplication. *Ann. Bot.* **2005**, *95*, 439–447. [CrossRef]
25. Amundson, S.; Deyton, D.E.; Kopsell, D.A.; Hitch, W.; Moore, A.; Sams, C.E. Optimizing Plant Density and Production Systems to Mazimize yield of greenhouse grown "Trust" Tomatoes. *HortTechnology* **2012**, *22*, 44–48. [CrossRef]
26. Carrillo, J.C.; Jimenez, F.; Ruiz, J.; Diaz, G.; Sanchez, P.; Perales, C.; Arellanes, A. Evaluación de densidades de siembra en tomate (*Lycopersicon esculentum* Mill) en invernadero. *Agron. Mesoam.* **2003**, *14*, 85–88. [CrossRef]

27. Grijalva-Contreras, R.L.; Macias-Duarte, R.; Valenzuela-Ruiz, M.; Robles-Contreras, F. Influence of plant density on yield and quality in tomatoes under greenhouse conditions in the Nortwest on Mexico (abstract). *HortScience* **2004**, *39*, 801–802. [CrossRef]
28. Grijalva-Contreras, R.L.; Macias-Duarte, R.; Duron, S.A.G.; Robles-Contreras, F. Evaluación de densidades y arreglos de plantación en tomate bola en condiciones de invernadero en el Noroeste de Sonora. *Biotecnica* **2010**, *11*, 20–28. [CrossRef]
29. Gunnlaugsson, B.; Adalsteinsson, S. Interlight and plant density in year-round production of tomato at Northern latitudes. *Acta Hortic.* **2006**, *711*, 71–76. [CrossRef]
30. Hochmuth, G.J. *Production of Greenhouse Tomatoes—Florida Greenhouse Vegetable Production Handbook*; University of Florida, IFAS: Gainesville, FL, USA, 2018; Volume 31. Available online: https://edis.ifas.ufl.edu/pdf/CV/CV266/CV266-4429807.pdf (accessed on 3 July 2023).
31. Freeman, J.H.; Frey, C.; Kanissery, R.; Smith, H.A.; Desaeger, J.; Vallad, G.E. Chapter 18. Tomato production. In *Vegetable Production Handbook of Florida*, 2022–2023 ed.; Dittmar, P.J., Agehara, S., Dufault, N.S., Eds.; University of Florida, IFAS: Gainesville, FL, USA, 2023; CV292. [CrossRef]
32. Johnson, G.; Ernest, J.E.; Adkins, M.J.; VanGessel, D.; Owens, J.; Jones, A.M.; Koehler, M.; Infante-Casella, W.; Kline, P.; Nitzsche, P.; et al. 2022/2023 Mid-Atlantic Commercial Vegetable Production Recommendations. Virginia Cooperative Extension. 456–420 (SPES-391P). 2022. Available online: https://www.pubs.ext.vt.edu/456/456-420/456-420.html (accessed on 3 July 2023).
33. Lamont, W.J., Jr.; Orzolek, M.D.; Holcomb, E.J.; Demchak, K.; Burkhart, E.; White, L.; Dye, B. Production system for horticultural crops grown in the Penn State High Tunnel. *HortTechnology* **2003**, *13*, 358–362. [CrossRef]
34. Zahid, B.; Ansari, R.; Cheema, M.J.M.; Anjum, L. Evaluation of deficit irrigation regime, row spacing and dual plantation of drip irrigated tomato under high tunnels. *J. Cent. Eur. Agric.* **2020**, *21*, 851–860. [CrossRef]
35. Reid, J.; Machanoff, C.; Tucker, C. Optimal spacing of grafted 'Primo Red' high tunnel tomato. *HortTechnology* **2023**, *33*, 381–386. [CrossRef]
36. Wells, O.S. Optimizing tomato yields in high tunnels. *HortScience* **1994**, *29*, 509–510. [CrossRef]
37. Saglan, N.; Yazgan, A. The effects of planting density and the number of trusses per plant on earliness, yield and quality of tomato grown under unheated high plastic tunnel. *Acta Hortic.* **1995**, *412*, 258–267. [CrossRef]
38. Rashid, A.; Rab, A.; Mohammad, H.; Ali, J.; Shahab, M.; Jamal, A.; Rehman, A.; Ali, M. Effect of row spacing and nitrogen levels on the growth and yield of tomato under walk-in polythene tunnel condition. *Pure Appl. Biol.* **2016**, *5*, 182–183. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.