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Response of Hydroponic Tomato Yield and Yield-correlated Morphological Characteristics to Constant or Growth Stage-based Nutrient Management Strategies

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Abstract. **In the United States, the annual revenue attributable to tomato production is \$1 billion. However, tomato production can cause negative environmental impacts, such as water pollution, often in the form of eutrophication-causing nutrient pollution. Hydroponic production can decrease excess nutrient leaching; however, optimization of nutrient management and cultivar choices could further decrease excess nutrient discharges. The objectives of this study were as follows: to evaluate and compare the responses of tomato growth characteristics, yield, and yield components to two nutrient management regimes (varying nutrient solution concentrations by growth stage and the use of a constant nutrient solution concentration from transplant to termination), and to analyze the effects of growth habits among six cultivars (Big Beef, Cherokee Purple, Heatmaster, Legend, Mountain Fresh Plus, and Tropic) on tomato yield and yield-correlated morphological characteristics. The nutrient management strategies were applied to tomato plants, and data regarding yield and related morphological characteristics were obtained. Data were analyzed using SAS PROC GLM. An analysis revealed no significant difference in the total fruit weight/plant between nutrient management regimes (P = 0.05); however, the mean fruit weight (164.26 g) and diameter (71.70 mm) were significantly greater (P < 0.0001) for plants that received the constant concentration nutrient regime. Indeterminate plants had a significantly greater (P < 0.0001) mean fruit weight (192.76 g) and mean fruit diameter (76.42 mm). Among cultivars, Big Beef had a significantly greater (P < 0.05) total fruit weight/plant (9.25 kg). Applying a constant nutrient concentration to indeterminate cultivars, particularly Big Beef and Cherokee Purple, improved the factors analyzed and could decrease negative environmental impacts while increasing profits of the producers.**

Tomatoes (*Solanum lycopersicum*) are an important food source. Globally, nearly five million hectares of agricultural land were involved in tomato production in 2020 (Food and Agriculture Organization of the United Nations 2023). According to the Food and Agriculture Organization (FAO), more than 185 million Mg of tomatoes were produced in 2020, thus making tomatoes a top 10 horticultural crop. In the United States, tomatoes are second among horticultural crops in terms of area of production (~110,000 ha) and yield (~10.9 million Mg). In the United States in 2018, the tomato crop was worth approximately \$2 billion, which is the greatest value among all vegetables grown in the country (US Department of Agriculture 2019).

Despite the great economic value of the US tomato crop, there are challenges such as increasing imports from Mexico, which could take as much as \$252 million away from domestic producers (Li et al. 2022). Additionally, hydroponic tomato production has been providing some off-season tomato production in the United States, and it has been profitable in some situations (Maureira et al. 2022). However, according to the study by Maureira et al. (2022), the main cost associated with off-season hydroponic tomato production was attributable to energy, and there seems to be possible savings related to nutrient optimization (Rosa-Rodríguez et al. 2020).

Agriculture comprises approximately 70% of freshwater usage, is the number one source of stream pollution, and is a top polluter of other surface water bodies and groundwater, especially because of excess nitrogen (N) and phosphorus (P). It is important to optimize agricultural practices to decrease the negative environmental impacts of food production (Frei et al. 2021; International Atomic Energy Agency 2016; Mateo-Sagasta et al. 2017). Researchers have explored strategies to optimize nutrient use to decrease excess nutrient discharge into the environment and found that relatively lower N levels than those that are sometimes used can decrease excess N discharge without impacting yield (Fan et al. 2024; Muñoz et al. 2008; Sun et al. 2019). Other studies have described the importance of optimizing nutrients for specific cultivars for particular growing environments (Abenavoli et al. 2016; Agele et al. 2008; Pendergrass and Best 2020). These studies showed the importance of optimizing nutrient usage in hydroponic tomatoes to obtain both economic and environmental benefits (Li et al. 2022; Maureira et al. 2022; Muñoz et al. 2008; Rosa-Rodríguez et al. 2020).

Nutrient concentrations and yield. Muñoz et al. (2008) studied the effects of decreased N input on NO_3^- leaching, on fruit weight, yield, and marketable fruit, and on the negative environmental impacts of tomato production using drip hydroponics in perlite bags. Their results indicated no significant differences in yield, mean fruit weight, or percentages of nonmarketable fruit across N applications ranging from 7 mM to 11 mM. When they assessed the environmental impact concerning eutrophication, the N application at 7 mM decreased the impact on eutrophication by two-thirds and greenhouse gas emissions by one-half.

Multiple researchers have reported that the use of lower levels of nutrients resulted in the same yield or an increased yield; furthermore, these reports have suggested that optimum nutrient levels should be sought (Etissa et al. 2013; Fontes et al. 2000; Hashida et al. 2014; Muñoz et al. 2008). Hashida et al. (2014) diluted the nutrient solution used in a hydroponic tomato experiment and found that this process significantly reduced the amount of N_2O released. Additionally, the reduction of their nutrient solution electrical conductivity (EC) from 2.3 during the first year to 1.3 during the second year increased the tomato yield per plant from approximately 0.5 kg to 0.9 kg (P < 0.05). Therefore, it seems possible that the greater levels of nutrients used in these studies either exceeded or were very near to the optimum threshold for one or more nutrients, and that decreasing these levels to values either closer to or below that threshold either increased or had no effect on tomato yield. Such optimum levels have been shown for N, P, and potassium (K) (Etissa et al. 2013; Fontes et al. 2000; Woldemariam et al. 2018). In hydroponic production specifically, increasing EC levels does not lead to increased

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Table 1. Nutrient concentrations (ppm) of three standard nutrient solutions.

Nutrient	Modified Steiner[i]	Hoagland and Arnon[ii]	Masterblend[iii]
Nitrogen	171	210	117
Phosphorus	48	31	47
Potassium	304	234	189
Calcium	180	160	114
Magnesium	48	34	39
Sulfur		64	48
Iron	3	2.5	2.4
Manganese	1–2	0.5	1.2
Boron	1	0.5	1.2
Zinc	0.4	0.05	0.3
Copper	0.2	0.2	0.3
Molybdenum	0.1	0.01	0.06

[i] Rutledge (1998).
[ii] Asao (2012).
[iii] Derived from Masterblend International (2018).

tomato yields if the EC levels increase to a value above a certain optimum level (Sonneveld and van der Burg 1991; Ullah et al. 2017). Based on the reported optimum levels of nutrients for tomato (Etissa et al. 2013; Fontes et al. 2000; Woldemariam et al. 2018), and on the reported optimum EC levels for tomato and other fruit crops (Sonneveld and van der Burg 1991; Ullah et al. 2017), identifying these optimums for tomato cultivars could lead to greater yields and potentially decrease the negative environmental impacts of production (Hashida et al. 2014; Muñoz et al. 2008).

Current recommendations for individual nutrient levels and the associated EC levels are not consistent (Asao 2012; Masterblend International 2018; Rutledge 1998). The concentrations of several nutrients range widely in three standard solutions used commercially and for research (Table 1). Additionally, some recommendations imply a constant concentration nutrient solution throughout most of the growing period, whereas others require a varied concentration nutrient solution (Table 2) based on growth stages (Heuvelink 2005; Masterblend International 2018; Rutledge 1998; The Ohio State University 2018).

Nutrient concentrations and cultivars. Nutrient optimization is also important at the cultivar level. To prevent chlorosis and blossom end rot, Pendergrass and Best (2020) showed that heirloom tomato cultivars, such as Vinson Watts German Pink, Cherokee Purple, and Willard Wynn's German Yellow, benefited from additional N, magnesium (Mg), and calcium (Ca) beyond standard tomato recommendations. There is evidence that nutrient optimization requirements vary among tomato cultivars, suggesting that some cultivars may tolerate lower N input levels (Abenavoli et al. 2016; Agele et al. 2008). Cultivar studies have also suggested the need to find optimum nutrient levels, whether to improve nutrient use efficiency or prevent deficiency-induced disorders, such as blossom end rot (Abenavoli et al. 2016; Agele et al. 2008; Pendergrass and Best 2020).

Objectives

Because of the contradictory information concerning appropriate nutrient concentrations within nutrient solutions used in hydroponic tomato production and conflicting advice concerning nutrient management regimes, as well as the general lack of information regarding cultivar-specific nutrient recommendations, it is necessary to analyze the effects of various nutrient management regimes on tomato yield and yield components. Therefore, the objectives of this study were as follows: to evaluate and compare the responses of tomato growth, yield, and yield components to nutrient management strategies, and to analyze the effects of growth habits and cultivars using six cultivars, Big Beef (BB), Cherokee Purple (CP), Heatmaster (HM), Legend (LG), Mountain Fresh Plus (MF), and Tropic (TP), on tomato yield and yield-correlated morphological characteristics.

Materials and Methods

Production details. This research was conducted at Tennessee Technological University's Oakley Greenhouse Complex (lat. 36.32151447385345, long. −85.28950893457912, 310 m elevation) between 22 Feb and 17 Jul 2023. The following six tomato (*Solanum lycopersicum*) cultivars, three determinate and three indeterminate, were used: BB and HM (Totally Tomatoes, Randolph, WI, USA); CP and MF (Johnny's Selected Seeds, Fairfield, ME, USA); LG (Tomato Growers Supply Company, Fort Myers, FL, USA); and TP (TomatoFest, Littleriver, CA, USA) (Table 3). All were planted into Riococo 300 (GB300-

Table 2. Nutrient concentrations (ppm) and electrical conductivity ($dS \cdot m^{-1}$) for growth-stage-based, varied-concentration nutrient solutions.

	Growth stage-based nutrient solution							
	Rutledge[i]					Jensen 3 Stage[ii]		
Nutrient, EC	S 1[iii]	S 2[iv]	S 3[v]	S 4[vi]	S 5[vii]	S 1[viii]	S 2[ix]	S 3[x]
Nitrogen	50	50–75	75–100	100–150	150–200	90	120	190
Phosphorus						47	47	47
Potassium						144	350	350
Calcium						144	160	200
Magnesium						60	60	60
Sulfur						10–200	10–200	10–200
Iron						2	2	2
Manganese						0.55	0.55	0.55
Boron						0.4	0.4	0.4
Zinc						0.33	0.33	0.33
Copper						0.05	0.05	0.05
Molybdenum						0.05	0.05	0.05
EC	0.6	0.6–0.7	0.7–0.9	0.9–1.8	1.8–2.2			

[i] Rutledge (1998).
[ii] Described by The Ohio State University (2018).
[iii] To the first true leaf.
[iv] To the third true leaf.
[v] To transplanting.
[vi] To the second cluster set.
[vii] To topping.
[viii] To the second truss open flowers.
[ix] To the fifth truss open flowers.
[x] Beyond the fifth truss.
EC = electrical conductivity; S = stage.

Table 3. Characteristics of studied tomato cultivars.

Cultivar	Growth habit	Hybrid	FW (g)	DTM
Big Beef	Indeterminate	Yes	255–454	73
Cherokee Purple	Indeterminate	No	227–340	72
Heatmaster	Determinate	Yes	198	75
Legend	Determinate	Yes	Large	68
Mountain Fresh Plus	Determinate	Yes	227–454	75
Tropic	Indeterminate	Yes	255	80

DTM = days to maturity; FW = fruit weight.

Fig. 1. The production area with 15-L coco coir grow bags placed in the troughs.

094-W) 15 L coco coir grow bags (Riococo Worldwide, Ceyhinz Link, Irving, TX, USA) on 22 Feb 2023, with three plants in each bag. The experiment was performed in an approximately 1100-m^2 gutter-connected greenhouse at the Oakley Greenhouse Complex. The greenhouse and rows were oriented approximately east to west. Rows were spaced 1.5 m apart, and the plants were approximately 0.3 m apart within rows. The greenhouse and grow bag setup before planting are shown in Fig. 1. The greenhouse was heated at night, with temperatures maintained above 10 °C. During the summer, houses were ventilated using sidewall curtains, a top vent along the peak of each of the four bays, and one fan/vent system per bay. Kool Ray Liquid Shade (Continental Products, Mayfield Heights, OH, USA) was applied on 30 May 2023 and 31 May 2023 to create approximately 33% shade. Temperature and humidity data were collected using a Govee Hygrometer Thermometer H5074 (Govee, Blue Island, IL, USA) (Table 4). Regular cultural practices, such as pruning and trellising (Fig. 2), were performed weekly, and the indeterminate plants were trained to one main stem. The determinate plants were pruned until the axillary shoot below the first inflorescence; then, side shoots and leaves were pruned only as necessary for light infiltration and airflow.

Nutrient management regimes. Two nutrient management regimes were applied: varying nutrient solution concentrations by growth stage (GSB) and a constant nutrient solution concentration (CN) from transplant to termination. The nutrient concentrations used for these stages were based on recommendations developed by Jensen of the University of Arizona but adjusted for the inputs used in this study (The Ohio State University 2018).

Table 4. Monthly mean of the minimum temperature (Tmin) and maximum temperature (Tmax) and relative humidity (RH) inside the Oakley greenhouse for the growing season of 23 Feb to 17 Jul 2023.

	Tmin	Tmax	RHmin	RHmax
Month	°C		%	
April	17.4 ± 1.1	30.3 ± 4.6	44.1 ± 5.1	82.1 ± 4.5
May	16.5 ± 1.2	35.6 ± 3.0	45.2 ± 4.4	92.9 ± 0.9
June	16.6 ± 1.7	34.1 ± 2.7	50.2 ± 4.4	92.6 ± 0.8
July[i]	20.0 ± 1.2	37.0 ± 2.6	48.8 ± 4.2	93.8 ± 0.5

[i] July mean only includes 17 d before termination of experiment.

Stage 1 was defined from transplant to the time that 75% of the plants had greater than two trusses with at least one open blossom. Stage 2 was from the end of stage 1 to the time when 75% of the plants had more than five open blossoms. Stage 3 was from the end of stage 2 until the end of the experiment. The hydroponic nutrient solution was delivered via a venturi-style injection system (Fig. 3) and drip irrigation system with three spikes in each bag. The spikes were attached to pressure-compensating emitters that discharged 1.9 L·h^{-1}.

Concentrations of N, K, Ca, and Mg were increased based on the growth stages, and sulfur (S) and chlorine (Cl) were increased as byproducts of this process (Table 5). All other nutrients remained the same throughout each stage. Masterblend Tomato Formula 4-18-38 (Masterblend International, LLC, Morris, IL, USA), magnesium sulfate ($MgSO_4$), calcium nitrate [$Ca(NO_3)_2$], calcium chloride ($CaCl_2$), and potassium sulfate (K_2SO_4) were used to provide the nutrients.

Experimental design. In the randomized complete block design, the plants were arranged in two zones, with one zone receiving GSB and the other receiving CN. Each zone contained one row of determinate plants (Fig. 4A) and one row of indeterminate plants (Fig. 4B), with 27 plants in each row. The rows were further divided into three replications, with each replication containing nine plants (three of each cultivar for each growth habit). Three plants of a single cultivar were randomly placed into coco coir bags (Fig. 3).

Measurements and data analysis. After the first ripe fruits, yield was assessed twice per week. For each plant, the fruits were counted, weighed, and measured for diameter. Trusses of the indeterminate plants were assessed weekly with counts of the number of trusses per plant and the number of trusses with at least one open blossom. The experiment was ended on 17 Jul 2023. Data were analyzed with PROC GLM (SAS version 9.4; SAS Institute, Cary, NC, USA) for continuous data, and Tukey's post hoc comparisons were performed when necessary to determine significant differences. PROC GENMOD was used to determine the Poisson distribution of discrete data ($\alpha = 0.05$), and the Bonferroni method was used to analyze significant differences (Orelien n.d.). Log transformation of the data was performed when necessary to meet test assumptions. Pearson correlations were analyzed with PROC CORR. Correlations were defined as very strong ($r \geq 0.8$), strong ($0.6 \leq r < 0.8$), moderate ($0.4 \leq r < 0.6$), weak ($0.2 \leq r < 0.4$), or very weak to no correlation ($0 \leq r < 0.2$).

Results

We grew six different tomato cultivars (three of determinate and three of indeterminate growth habits) in two different nutrient management regimes, GSB, which included varied nutrient solution concentrations by growth stage, and CN, which used the same nutrient solution concentration from transplant

Fig. 2. Trellised and pruned tomato plants shown at 18 d after transplant.

to termination. For each plant, we collected information regarding the total fruit weight, mean fruit weight, number of fruits, mean fruit diameter, and days to maturity. Data regarding the number of trusses for the indeterminate plants were also collected. Additionally, the number of fruits was divided by the number of trusses to produce a mean fruit number/truss for each plant. We did this to compare the responses of yield and yield-correlated morphological characteristics to the GSB and CN regimes, as well as to different growth habits and cultivars.

Differences in total fruit weight/plant. Yield was determined by analyzing the total fruit weight/plant. The difference in total fruit weight/plant, as affected by the studied factors, is shown in Table 6. The results indicated no significant difference in total fruit weight/plant between nutrient regimes ($P = 0.68$) or growth habits ($P = 0.75$). However, there were significant differences among cultivars ($P = 0.05$). BB produced total fruit weight/plant that was significantly greater than that of all other cultivars. ‘CP’, ‘HM’, ‘LG’, and ‘MF’ did not produce significant differences in the total fruit weight/plant, but all except ‘HM’ had a greater total fruit weight per plant than ‘TP’, which produced the least total fruit weight/plant ($P = 0.05$).

Correlations between total fruit weight/plant and morphological characteristics. The correlations between total fruit weight/plant and morphological characteristics revealed varying strengths of correlation for determinate plants alone and for both growth habits together; however, moderate to strong correlations existed for indeterminate plants alone (Table 7). For indeterminate plants, the number of fruits/plant was most strongly correlated with total fruit weight/plant (r = 0.79). The mean fruit weight and the number of clusters/plant were equally correlated (r = 0.68) with fruit weight/plant. The next strongest correlation was for mean fruit diameter (r = 0.59). However, for determinate plants, the number of fruits/plant (r = 0.69) was the only characteristic strongly correlated with the total fruit weight/plant. There were no strong correlations and only one moderate correlation (number of fruits per plant; r = 0.53) when considering the correlations between total fruit weight/plant and both growth habits together. Considering the correlations that existed between all other factors, there were very strong correlations between the mean fruit weight and mean fruit diameter for all plants (r = 0.98), determinate plants (r = 0.95), and indeterminate plants (r = 0.96). Indeterminate plants also had a strong correlation (r = 0.65) between the number of fruits/plant and the number of clusters/plant. As noted, cluster data were only collected for indeterminate plants.

Differences in the number of fruits/plant and in mean fruit weight. For indeterminate plants, fruits/plant had the strongest correlation with total fruit weight/plant (r = 0.79) (Table 7); however, the treatments in this study produced no significant differences in fruits/plant (Table 8). The nutrient regimes (GSB and CN) were not significantly different ($P = 0.98$), and neither were the growth habits (determinate and indeterminate) ($P = 0.36$). Our analysis also found no significant differences for the number of fruits/plant among cultivars.

The mean fruit weight had a strong correlation (r = 0.68) with total fruit weight/plant, and this analysis revealed that all the treatments used during this study led to significant differences in the mean fruit weight (Table 9). Concerning the nutrient management regimes, the mean fruit weight for CN (164.26 g) was significantly ($P < 0.0001$) greater than that for GSB (140.80 g). A greater mean fruit weight was recorded for plants with an indeterminate growth habit (192.76 g) compared to that of those with a determinate growth habit (112.29 g) ($P < 0.0001$). Considering cultivars, both BB (208.45 g) and CP (222.64 g) were similar but had the

Fig. 3. Determinate tomato plants (bottom left row) soon after transplant into coco coir bags. The nutrient injection system can be seen in the background.

Table 5. Approximate nutrients concentrations provided by growth stage.

	Nutrients (mg·L^{-1})[i]												
Stages	N	P	K	Ca	Mg	S	Cl	Fe	Mn	Zn	Cu	B	Mo
1: up to >2 trusses	117	47	189	114	39	48	0	2.4	1.2	0.3	0.3	1.2	0.06
2: >2 to >5 trusses	125	47	350	160	60	140	65	2.4	1.2	0.3	0.3	1.2	0.06
3: >5 trusses to end	190	47	350	203	60	140	0	2.4	1.2	0.3	0.3	1.2	0.06

[i] Concentrations were derived from Jensen (The Ohio State University 2018) and have been adjusted and rounded.

B = boron; Ca = calcium; Cl = chloride; Cu = copper; Fe = iron; K = potassium; Mg = magnesium; Mn = manganese; Mo = molybdenum; N = nitrogen; P = phosphorus; S = sulfur; Zn = zinc.

Fig. 4. (**A**) Determinate tomato plants with fruit at 48 d after transplant. (**B**) Indeterminate tomato plants with fruit at 48 d after transplant.

greatest mean fruit weight (P < 0.05), and TP (147.19 g) was significantly different from all others. On the lower end, both MF (120.70 g) and HM (119.35 g) had significantly greater mean fruit weight than LG (96.84 g), which had the smallest mean fruit weight of all the cultivars.

Differences in the number of clusters/plant for indeterminate plants. The number of clusters/plant, which was also strongly correlated (r = 0.68) (Table 7) with total fruit weight/plant, was significantly affected only by cultivar (Table 10). No difference was observed between nutrient management regimes (P = 0.57), and there was no comparison between growth habits because the count of the number of clusters/plant was only collected for plants of indeterminate growth habit. Among the three indeterminate cultivars, BB produced more clusters/plant (18) than TP (14) (P < 0.05). The cultivar CP (15) was not significantly different from either BB or TP regarding the number of clusters/plant.

Table 6. Differences in total fruit weight/plant (kg) by nutrient, growth habit, and cultivar.

Factor	Level	Mean (kg)	95% LCL	95% UCL	Pr > f
Nutrient					0.68
	GSB	7.00	6.48	7.53	
	CN	6.85	6.33	7.38	
Growth habit					0.75
	Det	6.87	6.34	7.39	
	Ind	6.99	6.46	7.51	
Growth (cultivar)					<0.0001
	Ind, Big Beef	9.25 a	8.34	10.16	
	Ind, Cherokee Purple	7.23 b	6.32	8.14	
	Det, Heatmaster	6.08 b,c	5.17	6.99	
	Det, Legend	7.25 b	6.34	8.16	
	Det, Mountain Fresh Plus	7.28 b	6.37	8.19	
	Ind, Tropic	4.48 c	3.57	5.39	

Different letters within the "mean" column represent significant differences (P < 0.05) among levels with the corresponding factor.

CN = nutrients were applied at a constant concentration regardless of growth stage; Det = determinate; Growth (cultivar) = cultivar nested within growth habit; GSB = nutrients were applied at concentrations that varied with growth stage; Ind = indeterminate; LCL = lower confidence limit; Pr > f = P values (P < 0.05); UCL = upper confidence limit.

Differences in mean fruit diameter. The mean fruit diameter was moderately correlated (r = 0.59) with total fruit weight/plant and showed significant differences in the response to the factors considered during this study (Table 11). A statistical analysis indicated that CN produced a significantly greater mean fruit diameter (71.70 mm) than GSB (68.02 mm) (P < 0.0001). Additionally, a greater mean fruit diameter was observed for indeterminate plants (76.42 mm) compared with that for determinate plants (62.14 mm) (P < 0.0001). Among cultivars, CP (83.68 mm) had a significantly greater mean fruit diameter than that of BB (77.39 mm), which had a significantly greater mean fruit diameter than that of TP (68.21 mm) and HM (64.58 mm). 'TP' had a significantly greater mean fruit diameter than that of 'MF' (62.69 mm) and 'LG' (59.14 mm), which had the smallest mean fruit diameter.

Measurements of mean fruit diameter allowed for the determination of the proportion of each tomato size based on US Department of Agriculture (USDA) standards (US Department of Agriculture 1997). According to the USDA, the minimum size for a large tomato is 63.5 mm (2.5 inches), and that for an extra-large tomato is 69.85 mm (2.75 inches). For the purposes of this study, a small tomato was considered to have any diameter less than 63.5 mm, an extra-large tomato was considered to have any diameter greater than 69.85 mm, and a large tomato was considered to have any diameter in between those values. The nutrient management regime led to significant differences in the total weights of small (P = 0.0001) and extra-large (P = 0.03) tomatoes, but not in those of large tomatoes (Table 12). GSB produced a mean weight of 1803.20 g for small tomatoes, whereas CN produced a mean weight of 1125.70 g for small tomatoes. However, CN produced a mean weight of 4911.69 g for extra-large tomatoes, whereas GSB produced a mean weight of 4313.15 g for extra-large tomatoes. The differences in the weights of small, large, and extra-large tomatoes were significant for growth habit (P < 0.0001). Determinate plants produced a significantly greater mean weight for small (2361.98 g; P < 0.05) and large (1127.13 g; P < 0.05) tomatoes, whereas indeterminate plants produced a greater mean weight for extra-large (5846.63 g) tomatoes. There were several significant differences among cultivars for the weights of each tomato size, with LG and MF producing significantly (P < 0.05) greater weights for small (3317.17 g and 2168.22 g,

Table 7. Correlation coefficients for fruit weight/plant and other morphological characteristics.

	DM	CP^{-1}	FC^{-1}	FP^{-1}	FD	MFW
CP^{-1}	—					
	—					
	−0.32*					
FC^{-1}	—	—				
	—	—				
	−0.27*	0.10				
FP^{-1}	−0.05	—	—			
	−0.17	—	—			
	−0.39**	0.65****	0.81****			
FD	−0.39****	—	—	−0.43****		
	0.02	—	—	−0.45***		
	−0.52****	0.23	−0.15	0.03		
MFW	−0.38****	—	—	−0.42****	0.98****	
	0.03	—	—	−0.50****	0.95****	
	−0.47***	0.31*	−0.10	0.11	0.96****	
FWP^{-1}	−0.32***	—	—	0.53****	0.26**	0.31**
	−0.12	—	—	0.69****	0.01	0.05
	−0.55****	0.68****	0.51****	0.79****	0.59****	0.68****

CP^{-1} = clusters/plant; DM = days to maturity; FC^{-1} = fruits/cluster; FD = fruit diameter; FP^{-1} = fruits/plant; FWP^{-1} = fruit weight/plant; MFW = mean fruit weight.

**** $P < 0.0001$; *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$.

In each block, the top number is the correlation including all plants, the second number is the correlation including only determinate plants, and the third number is the correlation including only indeterminate plants.

respectively) and large (1433.61 g and 1085.89 g, respectively) tomatoes, and BB and CP producing significantly ($P < 0.05$) greater weights for extra-large (7996.39 g and 6615.11 g, respectively) tomatoes.

Discussion

Main findings. Yield is an important measure for producers, and nutrient pollution from agricultural production, such as pollution from open hydroponic systems, is a threat to groundwater and surface water systems (Frei et al. 2021; Kumar and Cho 2014). Avoiding the use of excess nutrients and optimizing production by choosing the most efficient cultivars can help limit the negative effects of agricultural production on the environment (Abenavoli et al. 2016; Agele et al. 2008; Hashida et al. 2014; Muñoz et al. 2008; Pendergrass and Best 2020). This research focused on the response of tomato yield and yield-correlated morphological characteristics to the following factors: nutrient management regime, plant growth habit, and cultivar. There were two nutrient management regimes, GSB, which used varied nutrient solution concentrations across three plant growth stages, and CN, which used the same nutrient solution concentration regardless of growth stage. There were two growth habits, determinate, represented by the HM, LG, and MF cultivars, and indeterminate, represented by the BB, CP, and TP cultivars. We found significant differences for all studied factors for mean fruit weight and mean fruit diameter and among cultivars for total fruit weight per plant and clusters per plant.

Among those significant differences, there were three main findings. The first main finding was that the application of nutrients at a constant concentration, regardless of tomato plant growth stage, was preferable to increasing the nutrients with the growth stage. Second, concerning growth habit, the use of indeterminate plants seemed preferable to determinate plants. Third, BB and CP had the greatest yield and tomato size among the cultivars studied within the drip hydroponics system used in this study and regardless of the nutrient regime. Concerning these findings, one limitation of this study was that all findings arose from producing the six particular studied cultivars in a drip hydroponic production system using coco coir as a growing medium in a greenhouse in the humid subtropical climate of middle Tennessee. These and other study specifics should be considered before generalizing study results to a different production system or region.

Main finding 1: Constant concentration nutrient management was preferable. The primary goal of this study was to evaluate the responses of tomato yield and yield components to different nutrient management regimes. Our conclusion was that applying nutrients at a constant concentration across all growth stages was preferable to applying varying nutrient concentrations across growth stages. One point of evidence for this conclusion was that there was no significant difference ($P = 0.68$) in total fruit weight/plant (Table 6) between plants that received the CN nutrient management regime (6.85 kg) and those that received the GSB regime (7.00 kg). There were also no significant differences ($P = 0.98$) in the number of fruits/plant (Table 8) between CN (n = 45) and GSB (n = 58) and between the number of clusters/plant ($P = 0.57$) (Table 10) between CN (n = 15) and GSB (n = 16). This lack of difference between the nutrient regimes did not allow us to prove the null hypothesis to confirm that there were absolutely no differences between the nutrient management regimes. However, the fact that this study failed to reject the null hypothesis in this case did provide a point of evidence that there may not be a need to increase nutrient concentrations with the growth stage to produce the greatest total yield by total fruit weight and number while using the least amount of nutrients.

The failure to reject the null hypothesis that there was no difference between nutrient management regimes for the total fruit weight/plant, the number of fruits/plant, and the number of clusters/plant is worth further study; however, the primary reasons for recommending CN over GSB are related to the significant differences in the fruit characteristics. The mean fruit weight (Table 9) was significantly greater ($P < 0.0001$) with CN (164.26 g) than with GSB (140.80 g). The mean fruit diameter (Table 11) was also significantly greater ($P < 0.0001$) with CN (71.70 mm) than with GSB (66.86 mm). The difference in fruit diameter with CN (4911.69 g) resulted in a significantly greater ($P = 0.03$) weight of extra-large fruit (Table 12) than that with GSB (4313.15 g). However, GSB (1803.20 g) resulted in a significantly greater ($P = 0.0001$) weight of small fruit compared to that with CN (1125.70 g). The significantly greater weight of large fruits with CN and small fruits with GSB allowed for higher market prices for fruit grown with CN compared to the prices for fruit grown with GSB (US Department of Agriculture n.d.). Additionally, smaller fruits were sold at cull prices to local consumers. The results of this study indicated the potential for greater weights of more marketable fruits while using an overall lower level of nutrients, and this potential suggests that CN was a preferable nutrient regime compared to GSB. In practice, using CN could benefit

Table 8. Differences in fruits/plant by nutrient, growth habit, and cultivar.

Factor	Level	Mean	95% LCL	95% UCL	Pr > f
Nutrient					0.98
	GSB	58	49	68	
	CN	45	35	54	
Growth					0.36
	Det	67	57	76	
	Ind	36	27	46	
Growth (cultivar)					
	Ind, Big Beef	45	28	61	
	Ind, Cherokee Purple	33	16	49	
	Det, Heatmaster	51	35	68	
	Det, Legend	87	71	104	
	Det, Mountain Fresh Plus	61	45	78	
	Ind, Tropic	31	14	47	

CN = nutrients were applied at a constant concentration regardless of growth stage; Det = determinate; Growth (cultivar) = cultivar nested within growth habit; GSB = nutrients were applied at concentrations that varied with growth stage; Ind = indeterminate; LCL = lower confidence limit; Pr > f = P values ($P < 0.05$); UCL = upper confidence limit.

Table 9. Differences in mean fruit weight (g) by nutrient, growth habit, and cultivar.

Factor	Level	Mean (g)	95% LCL	95% UCL	Pr > f
Nutrient					<0.0001
	GSB	140.80 b	134.19	147.41	
	CN	164.26 a	157.65	170.86	
Growth					<0.0001
	Det	112.29 b	105.69	118.90	
	Ind	192.76 a	186.15	199.37	
Growth (cultivar)					<0.0001
	Ind, Big Beef	208.45 a	197.00	219.89	
	Ind, Cherokee Purple	222.64 a	211.19	234.08	
	Det, Heatmaster	119.35 c,d	107.90	130.79	
	Det, Legend	96.84 d	85.39	108.28	
	Det, Mountain Fresh Plus	120.70 c	109.26	132.15	
	Ind, Tropic	147.19 b	135.74	158.64	

Different letters within the "mean" column represent significant differences ($P < 0.05$) among levels within the corresponding factor.

CN = nutrients were applied at a constant concentration regardless of growth stage; Det = determinate; Growth (cultivar) = cultivar nested within growth habit; GSB = nutrients were applied at concentrations that varied with growth stage; Ind = indeterminate; LCL = lower confidence limit; Pr > f = P values ($P < 0.05$); UCL = upper confidence limit.

the environment via the use of lower nutrient levels and increase producer profit.

Other studies have found similar results concerning nutrient concentrations and yield. Muñoz et al. (2008) found that decreasing N levels from 11 mM to 7 mM in nutrient solution provided to the Bond tomato cultivar produced no significant differences in marketable yield, mean fruit weight, or proportions of nonmarketable fruits. During another production cycle, they found that further decreasing N levels from 7 mM to 5 mM also produced no significant differences in marketable yield or proportions of nonmarketable fruits. However, their lower N level produced significantly lower mean fruit weights, which was different from the results of the current study. This difference may be explained by the 5-mM level of N used by Muñoz et al. (2008), which was much lower than the lowest N level used during the present study. Their lower mean fruit weight with 5 mM N may also suggest that there was some threshold or optimum, and that adding more nutrient above it produced little to no benefit. Such an optimum for tomato yield has been found for N, P, and K concentrations in tomato production (Etissa et al. 2013; Fontes et al. 2000). Additionally, Woldemariam et al. (2018) reported that increasing K levels above 150 $kg \cdot ha^{-1}$ led to decreased fruit weight/plant. Finally, Sonneveld and van der Burg (1991) showed that increasing EC levels above 2.5 decreased the mean tomato fruit weight; because CN had an EC of approximately 1.7 and GSB had an EC of approximately 2.6, this same issue could have decreased fruit weights in this study. Despite the agreement of several studies, the current results differed from those of Lu et al. (2022), who found the greatest fruit weight/plant and mean fruit weight at the highest nutrient solution concentrations, up to 4.5 EC; however, this difference may have arisen from their use of a cherry tomato cultivar. Our study did not analyze any cherry tomatoes. Differences in climate between Beijing, China, the location of the Lu et al. (2022) study, and Middle Tennessee (the location of this study) as well as the specific nutrients used in both studies to raise the EC also could have played roles.

Main finding 2: Indeterminate plants outperformed determinate plants. The second finding was that the use of indeterminate plants ('BB', 'CP', and 'TP') seemed preferable to the use of determinate plants ('HM', 'LG', and 'MF'). Although there were no differences in total fruit weight/plant (Table 6) or fruits/plant (Table 8) between growth habits, there were significant differences in the mean fruit weight (Table 9) and mean fruit diameter (Table 11). Fruits from indeterminate plants were heavier and wider than those from determinate plants. This allowed indeterminate plants to produce a significantly greater weight of extra-large fruits (5846.63 g) than that of determinate plants (3378.20 g).

Others have also found that indeterminate plants were superior to determinate tomato plants for greenhouse production (Cantliffe et al. 2009; Ognev et al. 2022). Cantliffe et al. (2009) studied four indeterminate cultivars and one determinate in a greenhouse setting and fertigated via drip irrigation. They found that the determinate cultivar produced yields (Tasti-Lee, 10.8 $kg \cdot m^{-2}$) that were half that of the best indeterminate cultivar (Tradiro, 27.1 $kg \cdot m^{-2}$). More specifically similar to this study, regarding mean fruit weight, Ognev et al. (2022) obtained heavier fruit weight for indeterminate tomato cultivar Makhitos (159.17 g), whereas the greatest mean fruit weight for marketable fruit among their determinate cultivars was for Primadonna (141.85 g). Ognev et al. (2022) grew their plants in soil but inside a greenhouse with drip irrigation.

Main finding 3: BB and CP produced the best yields. The third finding was that, among the six cultivars studied, BB and CP produced a greater fruit weight and larger fruit in the undercover drip hydroponic system used in this study. BB produced significantly greater ($P < 0.05$) total fruit weight per plant (Table 6) than that of the other studied cultivars. CP had fruits with a significantly larger ($P < 0.05$) diameter (Table 11) than that of the other studied cultivars. The mean fruit weight of BB and CP were not significantly different ($P < 0.05$) (Table 9), but both cultivars had a significantly heavier mean fruit weight than that of the other cultivars. The same was true for the total weight of extra-large fruits (Table 12). These results suggest that, among the six cultivars in this study, BB and CP were the most promising. Similarly, Maynard et al. (2001) found that BB had the greatest yield of their 15 studied cultivars, but they did not find that BB had the greatest mean fruit weight or mean fruit diameter, which could be explained by the particular cultivars used in their comparison, with none of the others used in the present study. Sfeir (2020) reported that CP had the second greatest yield as well as the second greatest mean fruit weight and size of their five studied cultivars, again, possibly different because of the specific cultivars compared. A possible limitation of the present study concerning the conclusions was that only six cultivars were studied, and only 18 plants of each cultivar were included in the experiment.

Morphological characteristic correlations. In addition to the three main findings of this study, the reported correlations between morphological characteristics can also provide useful information. Such correlations, especially as related to yield, are common for plant breeding programs that aim for yield improvements and are often combined with the analysis of broad-sense heritability. In this study, we used morphological characteristic correlations with yield to show how these characteristics relate to yield. We analyzed the differences arising from nutrient management regimes, growth habits, and cultivars for all characteristics that were recorded during this study,

Table 10. Differences in clusters/plant by nutrient, growth habit, and cultivar.

Factor	Level	Mean	95% LCL	95% UCL	Pr > f
Nutrient					0.57
	GSB	16	16	17	
	CN	15	15	16	
Growth (cultivar)					
	Ind, Big Beef	18 a	17	19	
	Ind, Cherokee Purple	15 a,b	15	16	
	Ind, Tropic	14 b	13	15	

Different letters within the "mean" column represent significant differences ($P < 0.05$) among levels within the corresponding factor.

CN = nutrients were applied at a constant concentration regardless of growth stage; Det = determinate; Growth (cultivar) = cultivar nested within growth habit; GSB = nutrients were applied at concentrations that varied with growth stage; Ind = indeterminate; LCL = lower confidence limit; Pr > f = P values ($P < 0.05$); UCL = upper confidence limit.

Table 11. Differences in mean fruit diameter (mm) by nutrient, growth habit, and cultivar.

Factor	Level	Mean (mm)	95% LCL	95% UCL	Pr > f
Nutrient					<0.0001
	GSB	66.86 b	65.70	68.02	
	CN	71.70 a	70.54	72.86	
Growth					<0.0001
	Det	62.14 b	60.98	63.30	
	Ind	76.42 a	75.26	77.58	
Growth (cultivar)					<0.0001
	Ind, Big Beef	77.39 b	75.38	79.40	
	Ind, Cherokee Purple	83.68 a	81.67	85.69	
	Det, Heatmaster	64.58 c,d	62.57	66.59	
	Det, Legend	59.14 e	57.13	61.15	
	Det, Mountain Fresh Plus	62.69 d,e	60.68	64.70	
	Ind, Tropic	68.21 c	66.20	70.21	

Different letters within the "mean" column represent significant differences ($P < 0.05$) among levels within the corresponding factor.
CN = nutrients were applied at a constant concentration regardless of growth stage; Det = determinate; Growth (cultivar) = cultivar nested within growth habit; GSB = nutrients were applied at concentrations that varied with growth stage; Ind = indeterminate; LCL = lower confidence limit; Pr > f = P values ($P < 0.05$); UCL = upper confidence limit.

but only the top four most yield-correlated were presented in detail. Although the data are not shown for the two least yield-correlated of the studied characteristics, the number of days to maturity (in this study, it was considered to be the date of the first ripe fruit not exhibiting blossom end rot) and the derived data of the mean number of fruits per truss varied significantly only by cultivar, which was expected.

Considering the correlation data presented for the characteristics, the findings of this study were similar to those reported by others. The number of days to maturity generally has a weak to moderate, and mostly negative, correlation with yield, as was the case in this study (−0.12 to −0.55) and in others (Hidayatullah et al. 2008; Meitei et al. 2014; Paul et al. 2014; Rai et al. 2017). The number of clusters/plant had a strong correlation (r = 0.68) with yield, which was also observed in some other studies (Buhroy et al. 2017; Monamodi and Lesang 2012). However, other studies found almost no correlation between the number of clusters/plant and yield (Kousar et al. 2021; Meena and Bahadur 2015; Meitei et al. 2014). Fruits/cluster was moderately (r = 0.51) associated with yield in this study, which was similar to the findings of Monamodi and Lesang (2012) and Paul et al. (2014). In other studies, fruits/plant was moderately to very strongly correlated with yield, which was similar to the findings of this study (r = 0.79) (Buhroy et al. 2017; Estañ et al. 2009; McGiffen et al. 1994; Mohanty 2003; Monamodi and Lesang 2012; Ritonga et al. 2018, 2019). The moderate correlation found in this study for fruit diameter (r = 0.59) was similar to that of some studies (Meitei et al. 2014; Ritonga et al. 2019) but stronger than that of other studies (Hidayatullah et al. 2008; Meena and Bahadur, 2015; Shankar et al. 2013). Finally, mean fruit weight had a strong correlation (r = 0.68) with yield in this study, which was similar to the findings of others (Al-Aysh et al. 2012; Estañ et al. 2009; Rai et al. 2017) but in contrast to the findings of studies that reported very strong negative correlations between mean fruit weight and yield (Mohanty 2003; Wessel-Beaver and Scott 1992).

Table 12. Differences in total fruit weight of small, large, and extra-large fruits by nutrient, growth habit, and cultivar.

Factor	Level	Small mean (g)	Large mean (g)	Extra-large mean (g)
Nutrient				
	GSB	1803.20 a	887.94	4313.15 b
	CN	1125.70 b	814.31	4911.69 a
Growth habit				
	Det	2361.98 a	1127.13 a	3378.20 b
	Ind	566.93 b	575.13 b	5846.63 a
Growth (cultivar)				
	Ind, Big Beef	546.17 c	708.33 b,c	7996.39 a
	Ind, Cherokee Purple	293.33 d	323.44 c	6615.11 a
	Det, Heatmaster	1600.56 b	861.89 b	3614.39 b,c
	Det, Legend	3317.17 a	1433.61 a	2495.44 c
	Det, Mountain Fresh Plus	2168.22 a,b	1085.89 a,b	4024.78 b
	Ind, Tropic	861.28 c	693.61 b,c	2928.39 b,c

Different letters within the "mean" column represent significant differences ($P < 0.05$) among levels within the corresponding factor.
CN = nutrients were applied at a constant concentration regardless of growth stage; Det = determinate; Growth (cultivar) = cultivar nested within growth habit; GSB = nutrients were applied at concentrations that varied with growth stage; Ind = indeterminate; LCL = lower confidence limit; Pr > f = P values ($P < 0.05$); UCL = upper confidence limit.

Findings summary. The findings of the present study suggest that it is possible, in some cases, to use a lower concentration of nutrients and achieve similar total yield and significantly greater mean fruit weight and diameter, thus translating to more extra-large fruits. Although the nutrient management regimes used in this study need to be analyzed across more cultivars and in more production system types, using the CN nutrient management regime could benefit the environment because of its use and discharge of lower levels of nutrients and improve producer profit by lowering costs related to nutrient inputs and increasing proportions of more marketable fruits. Recommendations concerning growth habits and cultivars also need more analyses in different systems and with different commercially important cultivars. However, the use of indeterminate cultivars, particularly BB and CP, could increase yield and proportions of extra-large fruits while maintaining the same or lower input levels. Again, focusing on better-performing cultivars can be beneficial to the environment and producer profit. In addition, it is important to analyze various combinations of nutrients and levels to gain insight into whether increasing particular nutrients, alone or in combination, would produce similar or different results than those observed during the present study.

Conclusion

During this study of hydroponic tomato production, the application of nutrients at a constant rate, as compared with a nutrient management regime of increasing nutrient levels with the growth stage, produced similar total fruit weight/plant, significantly greater mean fruit weight and diameter, and a significantly greater proportion of extra-large fruits. The results of this study also showed that tomato plants of indeterminate growth habit, particularly the BB and CP cultivars, were better-yielding and had higher ratios of extra-large fruits than the other cultivars analyzed. Together, these findings suggested that nutrient inputs and cultivar choices can be optimized to produce greater weights of more marketable fruits while using lower levels of nutrient inputs.

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