

Effect of Nitrogen Concentration on Compact Tomato and Pepper Plants during Production and Fruiting Phases

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ABSTRACT. The objective of this study was to compare the growth, quality, and yield of compact tomato (*Solanum lycopersicum*) and pepper (*Capsicum annuum*) plants using different nitrogen (N) concentrations from a complete fertilizer solution (15N–2.2P–12.5K with micronutrients). Two experiments were conducted in separate locations (Florida and Indiana). During each experiment, tomato and pepper plants were hand-irrigated during production phases that lasted 7 and 9 weeks, respectively, with fertilizer solutions containing 0, 50, 100, 150, or 200 mg·L⁻¹ N applied with each irrigation event (Expt. 1) or every other irrigation event (Expt. 2). In both experiments, the N concentration either increased or remained constant during a fruiting phase during which tomato and pepper plants were grown for an additional 8 and 10 weeks, respectively. Growth and yield results were generally similar between the two experiments. Overall, plants that received a lower N concentration during both production and fruiting phases tended to be shorter, had a smaller growth index, and produced a lower fruit yield compared to those treated with a higher N concentration. Plant greenness, measured as either SPAD index or chlorophyll concentration, was generally lower in plants that received a lower N concentration during the production phases and maintained a similar pattern during the fruiting phases. However, at the end of both experiments, the greenness of plants that received 0/150 mg·L⁻¹ N (concentrations used during production and fruiting phases, respectively) tended to be higher than that of those treated with 50/50 mg·L⁻¹ N. Fruit yield was generally lowest for plants from both species treated with either 0/150 or 50/50 mg·L⁻¹ N. In general, tomato plants treated with ≥100/100 mg·L⁻¹ N had a similar fruit yield. However, the yield of pepper plants tended to increase with higher N concentrations during both the production and fruiting phases. Intumescence of pepper plants also increased with a higher N concentration, but there were different responses between the two experiments, suggesting that the growing environment plays a role during the development of the disorder. Overall, our findings showed that reducing the initial N concentration is a potential strategy for producing short tomato and pepper plants with a small growth index, but that the postproduction yield will likely decrease as the N concentrations are reduced during production.

The high value and short production cycle of most bedding plants require intense production methods that often include the use of plant growth regulators to maintain desirable attributes for plant size, shape, and flowering (Jardin 2015). Growers typically aim to produce compact plants that are esthetically and proportionally balanced to the container size. Controlling shoot height is also important for shipping and handling after plants leave production facilities (Whipker et al. 2011). However, shoot-height control can be a challenge when growing plants of edible crops such as vegetables and herbs because of existing regulations with the use of chemical plant growth regulators. To date, uniconazole is

the only approved active ingredient for these crops, and its cumulative application cannot exceed 10 mg·L⁻¹; furthermore, it must be applied no later than 14 d after the two-to-four true-leaf stage (Dunn et al. 2022; Runkle 2009). Although various studies have evaluated nonchemical means to control the shoot height of ornamental plants, including mechanical conditioning (Latimer 1998), modifying light quality (Bridgen 2016; Feng et al. 2019; Rajapakse and Kelly 1992), restricting fertilizer applications (Ågren et al. 2012; Kang and van Iersel 2009; Latimer and Oetting 1998), adjusting day and night temperatures (Amsen and Nielsen 1991; Boldt 2018; Karlsson et al. 1989), applying controlled water deficit (Alem et al.

2015; Nemali and van Iersel 2004), and restricting root growth (van Iersel 1997), limited information describing the effect of nonchemical shoot-height control strategies for vegetable bedding plants is available (Currey et al. 2019, 2020; Litvin et al. 2016).

Tomato (*Solanum lycopersicum*) and pepper (*Capsicum annuum*) are popular vegetable bedding plants in the United States, with 86% and 46% of households, respectively, producing these plants in 2023 (Littlefield 2023). New compact cultivars of these crops have become available in recent years, thus enabling consumers to garden in small, urban spaces (Cruz and Gómez 2022; Cruz et al. 2023; Richardson and Arlotta 2022). However, recent studies have suggested that the dynamic environmental conditions in most greenhouses, such as temperature, humidity, and light quality, can largely affect growth of these plants and, thus, their natural compact habit may not be maintained (Cruz et al. 2022, 2023).

A common recommendation for growers to keep vegetable bedding plants short is to allow them to slightly wilt between irrigation events (Leth 2022). Another industry report recommended limiting excess nitrogen (N) to control shoot height (Carlson et al. 2020). Accordingly, various studies have shown that reducing the N concentration during greenhouse production can help control the shoot height of vegetable transplants (Liu et al. 2012) and various ornamental bedding plants (Harp and Pulatlic 2008; Park and Faust 2021, 2023; White and Scoggins 2005). Restricting other nutrient elements such as phosphorus (P) has also been demonstrated to limit the shoot height of potted herbs, such as parsley (*Petroselinum crispum*), sage (*Salvia officinalis*), basil (*Ocimum basilicum*), and dill (*Anethum graveolens*) (Currey et al. 2020), and ornamental plants such as poinsettia (*Euphorbia pulcherrima*) and chrysanthemum (*Chrysanthemum × morifolium*) (Caspersen and Bergstrand 2020). Although these strategies can help growers produce shorter plants, their postproduction effects are largely unknown. Dufault (1998) noted that fertilizer availability during transplant production directly affects yield of fruiting vegetables. Therefore, potential yield reductions from using these recommended practices during vegetable bedding plant

production may affect consumers' experiences in the postproduction environment (Kendal et al. 2012).

The objective of this study was to compare the growth, quality, and yield of compact tomato and pepper plants using different N concentrations from a complete fertilizer solution during the "production" and postproduction "fruiting" phases. We hypothesized that plants with lower N during the production phase would be shorter than those with higher N, but that intermediate N concentrations would enable the production of short, high-yielding plants during the fruiting phase. Two experiments were conducted in separate locations during this study.

Materials and methods

EXPT. 1. The first experiment was conducted in Gainesville, FL, USA (lat. 30°N), where seeds of compact 'Siam' (PanAmerican Seed Co., Chicago, IL, USA) tomato and ornamental/edible 'Basket of Fire' (Syngenta AG, Basel, Switzerland) pepper were individually sown on 30 Sep 2021 into industry-standard 84-cell propagation trays (individual cell volume, 25 mL) filled with horticultural grade substrate composed of (volume/volume) 79% to 87% peatmoss, 10% to 14% perlite, and 3% to 7% vermiculite (Pro-Mix BX general purpose; Premier Tech Horticulture, Quakertown, PA, USA) specially formulated without a fertilizer starter charge. Trays were placed on a metallic mesh bench [7.6 m (length) × 1.8 m (width)] inside a polycarbonate

greenhouse with retractable shade curtains that was equipped with unit heaters and pad-and-fan evaporative cooling. Pepper and tomato seedlings were grown for 15 and 30 d, respectively, and irrigated as needed with clear tap water with an electrical conductivity (EC) of 0.4 mS·cm⁻¹, pH of 8.3, and 31.2 mg·L⁻¹ calcium carbonate (CaCO₃), and that contained (in mg·L⁻¹) 0.3 N [combining 0.2 ammonium (NH₄-N) and 0.1 nitrate NO₃-N], 0.1 P, 1.7 potassium (K), 36.8 calcium (Ca), 23.4 magnesium (Mg), 41.6 sulfur (S), 0.02 iron (Fe), 0.0 manganese (Mn), 0.0 zinc (Zn), 0.0 copper (Cu), 0.03 boron (B), 0.0 molybdenum (Mo), 11.5 sodium (Na), and 27.3 chloride (Cl).

On 29 Oct 2021, 42 uniform seedlings of each species were individually transplanted into 8-inch-diameter (20.3 cm) azalea plastic containers (3.1 L) (BWI; Nash, TX, USA) using the same aforementioned substrate. Six additional tomato seedlings were transplanted using the same commercial substrate, but with a formulation that had a fertilizer starter charge (1.0 to 2.3 mS·cm⁻¹ EC according to the manufacturer label). Plants were randomly placed on two metallic mesh benches (one for each species) in the same aforementioned greenhouse and spaced 30 cm apart. Each plant was placed on top of an 8-inch plastic saucer to ensure that leachate was reabsorbed after each irrigation event.

Fertilizer treatments were started at the beginning of each production or fruiting phase. The production phase ended when all plants had at least one immature fruit ≥1 cm in diameter, which occurred on 19 Dec 2021 and 28 Dec 2021 for tomato and pepper plants, respectively (approximately 7 and 9 weeks after transplanting). During the production phase, the experiment used an unbalanced design to accommodate the treatments evaluated during the fruiting phase. Therefore, 18, 12, 6, and 6 replicate plants of each species were hand-irrigated with fertilizer solutions containing 50, 100, 150, or 200 mg·L⁻¹ N, respectively, provided by a water-soluble fertilizer with micronutrients (Peter's Professional 15N-2.2P-12.5K; ICL Specialty Fertilizer; Summerville, SC, USA) applied with every irrigation event. Six tomato plants were also grown in substrate with fertilizer starter charge

and were irrigated with tap water only (hereafter referred to as plants treated with 0 mg·L⁻¹ N). All plants were checked once daily, and irrigation events occurred as needed when the substrate moisture level of four replicate plants per treatment fell below level three based on a visual subjective moisture scale (Fisher 2013). Plants were hand-irrigated with a graduated cylinder, which enabled quantification of the volume of fertilizer solution applied until slight leaching was observed in the saucers.

During the fruiting phase, six replicate plants of each species were assigned a fertilizer treatment whereby the N concentration either increased or remained constant throughout the rest of the experiment. Eight fertilizer treatments were evaluated in this phase, and the treatment codes used from hereafter describe the N concentration (in mg·L⁻¹) applied during the production and fruiting phase, respectively: 0/150, 50/50, 50/100, 50/150, 100/100, 100/150, 150/150, or 200/200. The fruiting phases ended on 10 Feb 2022 and 9 Mar 2022 for tomato and pepper plants, respectively (8 and 10 weeks).

Temperature and relative humidity (RH) setpoints in the greenhouse were 24/22 °C (day/night) and 65%, respectively. Data were measured with temperature and RH probes (HMP60-L; Campbell Scientific, Logan, UT, USA) and quantum sensors (SQ512; Apogee Instruments Inc., Logan, UT, USA) interfaced to a datalogger (CR1000 with AM16/32B multiplexer; Campbell Scientific) placed at above-canopy height in the center of each bench. Measurements were performed every 30 s and recorded at 60-min intervals. The average (±SD) daily temperature, RH, and daily light integral (DLI) recorded throughout the experiment were 23.1 ± 1.2 °C, 65 ± 10%, and 16.3 ± 3 mol·m⁻²·d⁻¹, respectively.

EXPT. 2. The second experiment was conducted in West Lafayette, IN, USA (lat. 40°N), where seeds of the same species and cultivars were sown on 9 Sep 2022 into industry-standard 72-cell propagation trays (individual cell volume, 46 mL) filled with horticulture-grade substrate (Professional Growing Medium; Midwest Trading, Virgil, IL, USA) specially formulated without a fertilizer starter charge. The substrate was composed of (volume/volume) 70% to 76% peatmoss, 13% to 17% perlite,

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and 5% to 7% pine bark. Trays were placed on a metallic mesh bench [7.3 m (length) $\times$ 1.8 m (width)] inside a glass-glazed greenhouse with retractable shade curtains, pad-and-fan evaporative cooling, and radiant hot water pipe heating regulated by an environmental control system (Maximizer Precision 10; Priva Computers, Vineland Station, ON, Canada). Supplemental lighting was delivered by 1000-W high-pressure sodium lamps (P.L. Light Systems Inc., Beamsville, ON, Canada) used for 16 h·d⁻¹ (0500 to 1900 HR) that provided a photosynthetic photon flux density of approximately 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Seedlings were grown for 36 d and irrigated as needed with acidified tap water that had an EC of 0.8 mS·cm⁻¹, pH of 7.3, 195 mg·L⁻¹ CaCO₃, and containing (in mg·L⁻¹) 0.2 NO₃-N, 0.4 P, 3.0 K, 96.0 Ca, 38.0 Mg, 51.0 S, 0.4 Fe, 0.0 Mn, 0.0 B, 14 Na, and 36 Cl.

On 4 Oct 2022, 64 uniform seedlings of each species were individually transplanted and grown following procedures similar to those described for Expt. 1, with the following exceptions. Plants of both species were treated with 0 mg·L⁻¹ N, and the substrate used for this treatment was composed of 50% coarse peatmoss, 35% pine bark, and 15% horticultural perlite (BM7 35% North Bark; Berger, QC, Canada). Plants in all other treatments were grown in the same substrate used during propagation. As previously explained, an unbalanced design was used during the production phase, during which 8, 24, 16, 8, and 8 replicate plants of each species were hand-irrigated with fertilizer solutions containing 0, 50, 100, 150, and 200 mg·L⁻¹ N, respectively, applied every other irrigation event. Acidified tap water was used to irrigate plants on days when no fertilizer solution was applied. The production phase ended on 21 Nov 2022 and 5 Dec 2022 for tomato and pepper plants, respectively (7 and 9 weeks after transplanting). For the fruiting phase, eight replicate plants of each species were grown with the same fertilizer treatments evaluated during Expt. 1. The fruiting phases ended on 17 Jan 2023 and 13 Feb 2023 for tomato and pepper plants, respectively (8 and 10 weeks).

Temperature and RH setpoints in the greenhouse were 24/22 °C (day/night) and 65%, respectively. However, RH was difficult to maintain

within the desired setpoint because of the use of winter heating. Temperature sensors (107 Temperature Probe; Campbell Scientific) and quantum sensors (SQ-500-SS; Apogee Instruments) interfaced to a datalogger (CR1000; Campbell Scientific) were placed at above-canopy height in the center of each bench. RH was measured with a datalogger (HOBO UX100-023; Onset Computer Corporation, Bourne, MA, USA) that was also placed at the center of each bench. The average daily temperature, RH, and DLI recorded throughout the experiment were 23.4 $\pm$ 1.6 °C, 43 $\pm$ 9%, and 14 mol·m⁻²·d⁻¹, respectively.

DATA COLLECTION. Data collected were the same in both experiments, and variables of all plants were measured, with a few exceptions, as described subsequently. Before the end of each phase, plant height was measured from the substrate surface to the tallest growing point. The widest diameter and width 90° from the widest diameter were also recorded. The growth index (GI) was used as an indication of plant volume calculated using the formula $\pi \times h \times r^2$, where h is the plant height and r is calculated by multiplying $\frac{1}{2}$ times the mean of two plant diameters. This was immediately followed by a visual assessment of intumescence in pepper plants, which was noticeable under some fertilizer treatments. The intumescence incidence was measured by counting the number of leaves with intumescence on the third largest side-shoot from each plant and dividing that number by the total number of leaves within the same side shoot. Intumescence severity was also evaluated on the same side shoot using a subjective visual scale ranging from 0 to 10, where the percentage indicates the leaf area covered by intumescence as follows: 0 = no intumescence; 1 = 1% to 10%; 2 = 11% to 20%; 3 = 21% to 30%; 4 = 31% to 40%; 5 = 41% to 50%; 6 = 51% to 60%; 7 = 61% to 70%; 8 = 71% to 80%; 9 = 81% to 90%; and 10 = 91% to 100%. Intumescence data were collected for both the upper and lower surfaces of each side shoot.

Before the end of each phase, leaf greenness was measured using the soil plant analysis development (SPAD) index (Expt. 1) or chlorophyll concentration (Expt. 2). Data of fully

expanded leaves were collected using a SPAD meter (SPAD-502; Konica Minolta Sensing, Osaka, Japan) or a chlorophyll meter (MC-100; Apogee Instruments). Data were averaged based on three measurements per leaf. Substrate leachate EC and pH were measured at the end of each phase using a portable meter (HI9813-6; Hanna Instruments, Carrollton, TX, USA) following the pour-through method (LeBude and Bilderback 2009).

During Expt. 1, tomato and pepper plants were first harvested on 6 Jan 2022 and 18 Jan 2022, respectively. During Expt. 2, tomato and pepper plants were first harvested on 15 Dec 2022 and 6 Jan 2023, respectively. The first harvest occurred when all plants had at least three fully mature fruit, which was determined based on a full transition to red. After the first harvest, fruit were harvested weekly, and the number of mature fruit and fruit fresh weight (FW) were recorded each time until the end of the experiment. Three tomato fruit were randomly selected from the third harvest and sampled to determine Brix measurements using a digital refractometer (HDR-P; Thermo-Fisher Scientific, Waltham, MA, USA).

DATA ANALYSES. Both experiments used a completely randomized design whereby each plant was considered an experimental unit. Data were analyzed separately for each species and experiment. Data were subjected to an analysis of variance using statistical software (JMP Pro version 16; SAS Institute Inc., Cary, NC, USA), and treatment means were compared using Tukey's honestly significant difference test ($P \leq 0.05$).

Results and discussion

GROWTH AND QUALITY. Plants of both species were smaller when treated with a lower N concentration during both the production and fruiting phases (Tables 1 and 2). For example, during the production phase in both experiments, tomato plants that received no fertilizer or 50 mg·L⁻¹ N were shorter and had a smaller GI than those treated with 150 or 200 mg·L⁻¹ N. However, the height and GI of tomato plants that received 100, 150, or 200 mg·L⁻¹ N were similar. During both experiments, the shoot height and GI of pepper plants were generally lower as the N concentration decreased.

Table 1. Growth, plant greenness, and leachate electrical conductivity (EC) and pH measured during the production phase of compact ‘Siam’ tomato and ‘Basket of Fire’ pepper plants grown in a greenhouse for 7 and 9 weeks, respectively, using different fertilizer treatments in two experiments.

Nitrogen concn (mg.L ⁻¹)	Shoot ht (cm) ⁱ		Growth index (cm ³) ⁱⁱ		SPAD index ⁱⁱⁱ	Chlorophyll concn (μmol.m ⁻²)	EC (mS.cm ⁻¹)		pH	
	1 ^{iv}	2	1	2	1	2	1	2	1	2
Tomato										
0	21.9 c ^v	16.5 b	0.022 c	0.018 c	34.6 c	27.8 d	—	1.5 c	—	7.1 a
50	23.3 bc	16.8 b	0.035 b	0.020 bc	40.4 b	54.3 c	2.2 c	1.6 bc	5.9 a	7.1 a
100	25.3 abc	18.2 a	0.044 ab	0.025 ab	42.0 b	64.1 b	2.3 c	1.7 bc	5.8 a	7.0 a
150	27.0 ab	18.7 a	0.045 ab	0.029 a	42.0 b	67.1 ab	3.7 b	2.3 ab	5.6 b	7.0 a
200	27.3 a	18.8 a	0.052 a	0.030 a	47.8 a	71.0 a	5.4 a	2.6 a	5.3 c	6.8 b
Pepper										
0	—	23.2 d	—	0.025 d	—	7.9 d	—	1.6 b	—	7.0 a
50	25.1 c	34.7 c	0.024 d	0.069 c	40.4 b	27.8 c	1.6 b	1.7 b	5.8 a	5.7 b
100	28.4 b	37.6 bc	0.039 c	0.104 b	40.8 b	40.6 b	1.8 b	1.8 ab	5.7 ab	5.8 b
150	30.0 ab	41.1 ab	0.048 b	0.112 ab	43.3 ab	46.4 ab	2.0 b	2.1 ab	5.7 ab	5.7 b
200	32.3 a	48.4 a	0.057 a	0.137 a	43.6 a	51.0 a	2.9 a	2.5 a	5.6 b	5.1 c

ⁱ 1 cm = 0.3937 inches.

ⁱⁱ The growth index was calculated using the formula $\pi \times h \times r^2$, where h is plant height and r is calculated by multiplying 1/2 times the mean of two canopy widths.

ⁱⁱⁱ Leaf greenness was measured using a soil plant analysis development (SPAD) index and chlorophyll concentration in Expts. 1 and 2, respectively.

^{iv} Experiment number, where 1 = fertilizer treatments applied with every irrigation event in Gainesville, FL, USA, and 2 = fertilizer treatments applied every other irrigation event in West Lafayette, IN, USA.

^v For each species, means within column followed by the same letter are not different based on Tukey’s honestly significant difference test at $P \leq 0.05$.

During the fruiting phase, both tomato and pepper plants in Expt. 1 that received 0/150 or 50/50 mg·L⁻¹ N were shorter than those treated with 200/200 mg·L⁻¹ N (Table 2). However, the shoot height was similar among

plants from both species treated with $\geq 50/150$ mg·L⁻¹ N. The GI of tomato plants that received 0/150 mg·L⁻¹ N was approximately half that of plants treated with 200/200 mg·L⁻¹ N, which also produced a GI similar to that

of plants treated with 100/100, 100/150, or 150/150 mg·L⁻¹ N. Similarly, the GI of pepper plants was generally smaller as the N concentration decreased; additionally, during both experiments, the GI of plants treated

Table 2. Growth, plant greenness, and leachate electrical conductivity (EC) and pH measured during the fruiting phase of compact ‘Siam’ tomato and ‘Basket of Fire’ pepper plants grown in a greenhouse for 15 and 19 weeks, respectively, using different fertilizer treatments in two experiments.

Nitrogen concn (mg·L ⁻¹)	Shoot ht (cm) ⁱ		Growth index (cm ³) ⁱⁱ		SPAD index ⁱⁱⁱ	Chlorophyll concn (μmol·m ⁻²)	EC (mS·cm ⁻¹)		pH	
	1 ^{iv}	2	1	2	1	2	1	2	1	2
Tomato										
0/150 ^v	23.5 b ^{vi}	35.3 cd	0.032 d	0.074 cd	51.6 a	42.6 cd	3.1 c	2.8 c	5.1 de	6.9 bc
50/50	23.3 b	23.3 e	0.042 bcd	0.048 d	37.4 c	39.6 d	1.5 e	1.3 d	6.3 a	7.8 a
50/100	24.5 ab	32.5 d	0.044 abcd	0.062 d	45.9 abc	43.7 bcd	2.1 de	2.6 c	5.9 b	7.3 b
50/150	24.0 ab	38.5 bc	0.038 cd	0.086 cd	46.2 abc	49.0 ab	3.8 bc	2.7 c	5.3 cd	7.1 b
100/100	26.7 ab	43.9 a	0.060 ab	0.128 b	44.7 abc	44.8 bcd	2.3 d	2.5 c	5.8 b	7.1 b
100/150	25.5 ab	44.2 a	0.052 abc	0.110 bc	41.9 bc	51.9 ab	4.0 d	3.4 b	5.3 cd	6.9 bc
150/150	27.7 ab	43.1 a	0.061 ab	0.170 a	42.7 bc	57.9 a	4.5 b	3.9 b	5.1 e	6.7 c
200/200	28.5 a	42.7 ab	0.065 a	0.180 a	49.4 ab	57.6 a	6.7 a	5.0 a	4.6 f	6.5 c
Pepper										
0/150	—	20.8 d	—	0.030 d	—	34.7 b	—	3.0 cd	—	7.2 a
50/50	27.0 b	31.6 c	0.036 d	0.061 cd	13.8 b	8.3 e	1.1 f	2.5 d	6.2 b	7.0 b
50/100	29.8 b	31.0 c	0.057 cd	0.072 bcd	47.2 a	18.3 cd	1.6 ef	3.4 bc	6.5 a	7.1 ab
50/150	30.5 ab	34.1 bc	0.063 cd	0.086 abc	52.5 a	22.7 cd	3.5 c	3.9 b	5.9 c	7.2 a
100/100	30.7 ab	37.1 ab	0.069 cd	0.107 ab	49.4 a	14.4 de	2.1 de	3.6 b	6.4 ab	7.2 a
100/150	33.0 ab	37.0 ab	0.097 bc	0.115 ab	51.0 a	24.8 c	4.4 b	3.9 b	5.5 d	7.2 a
150/150	32.3 ab	35.2 bc	0.112 b	0.123 a	51.8 a	25.2 c	4.8 b	4.0 b	5.6 cd	7.2 a
200/200	37.2 a	41.0 a	0.163 a	0.124 a	50.8 a	55.4 a	7.0 a	5.4 a	4.9 e	7.2 a

ⁱ 1 cm = 0.3937 inches.

ⁱⁱ The growth index was calculated using the formula $\pi \times h \times r^2$, where h is plant height and r is calculated by multiplying 1/2 times the mean of two canopy widths.

ⁱⁱⁱ Leaf greenness was measured using a soil plant analysis development (SPAD) index and chlorophyll concentration in Expts. 1 and 2, respectively.

^{iv} Experiment number, where 1 = fertilizer treatments applied with every irrigation event in Gainesville, FL, USA, and 2 = fertilizer treatments applied every other irrigation event in West Lafayette, IN, USA.

^v Numbers represent the concentrations used during the production and fruiting phases, respectively.

^{vi} For each species, means within column followed by the same letter are not different based on Tukey’s honestly significant difference test at $P \leq 0.05$.

with 50/50 mg·L⁻¹ N was smaller than that of plants that received 100/150, 150/150, or 200/200 mg·L⁻¹ N. In Expt. 2, tomato plants that received 50/50 mg·L⁻¹ N were the shortest, whereas the shoot height was similar among those treated with 100/100, 100/150, 150/150, or 200/200 mg·L⁻¹ N. Tomato plants that received 0/150, 50/50, 50/100, or 50/150 mg·L⁻¹ N also had a smaller GI than those treated with $\geq 100/100$ mg·L⁻¹ N.

It is likely that growth differences were not only caused by direct treatment effects but also caused by indirect changes in plant growth. Specifically, the different N concentrations likely had a compounding effect on growth, particularly during the production phase when plants mostly produced vegetative tissues. Larger plants received more frequent irrigation to sustain their higher transpirational demand, which increased the applied N concentration, thus further increasing their growth.

Our findings are consistent with those of others who have evaluated the effect of fertilizer concentration during the production of ornamental bedding plants (Bergstrand 2022; Gao et al. 2023). Harp and Pulatic (2008) found that both the height and width of ornamental white clover (*Trifolium repens*) linearly decreased as the N concentration decreased from 300 to 0 mg·L⁻¹. More recently, Park and Faust (2023) reported that as the N concentration decreased from 200, 100, or 50 mg·L⁻¹ to 0 mg·L⁻¹, petunia (*Petunia $\times$ hybrida*) plants were 75%, 70%, or 57% shorter, respectively. However, limited information describing fertilization strategies during the production of compact fruiting vegetables is available (Carlson et al. 2020). Cruz et al. (2022, 2023) reported that the GIs of 'Siam' tomato and 'Basket of Fire' pepper plants grown in a greenhouse using 150 mg·L⁻¹ N were 0.05 cm³ and 0.03 cm³, respectively. These values were much lower than those measured during our study when plants were treated with 150/150 mg·L⁻¹ N (Table 1). It is plausible that the differences in the GI observed during our study and those observed by Cruz et al. (2022, 2023) were attributable to environmental differences because the average DLIs in our experiments were approximately 20% to 30% higher than those reported in their study.

Researchers who evaluated the fertilization effects on field-grown vegetable plants have also shown that reducing the N concentration results in shorter plants (Aminifard et al. 2012a; Prasad et al. 2016). For example, Ayodele et al. (2015) reported that decreasing the N concentration from 150 to 0 mg·L⁻¹ resulted in 33% shorter pepper plants. Similarly, Etissa et al. (2013) reported that reducing the N concentration from 150, 100, and 50 mg·L⁻¹ to 0 mg·L⁻¹ resulted in 23%, 19%, and 14% shorter tomato plants, respectively. Although these studies were performed in the field using tomato and pepper cultivars that were different from the ones used in our study, their findings aligned with ours and those of others (Bergstrand 2022; Carlson et al. 2020; Gao et al. 2023; Harp and Pulatic 2008; Park and Faust 2023), thus confirming that, in general, decreasing the N concentration in the fertilizer solution will help produce shorter plants.

As expected, both SPAD index and chlorophyll concentration were lower as N concentration decreased during the production phase (Table 1). For example, the SPAD index in Expt. 1 was lowest for tomato plants that received no fertilizer and highest for those treated with 200 mg·L⁻¹ N. However, the SPAD index values of pepper plants that received 50 or 100 mg·L⁻¹ N were similar and lower than those of plants treated with 150 or 200 mg·L⁻¹ N. In Expt. 2, there was a general trend of decreasing chlorophyll concentrations with lower N concentrations applied to plants of both species. Our findings are similar to those of others who have shown that decreasing N concentrations will reduce the SPAD index or chlorophyll concentration of pepper (Aminifard et al. 2012a, 2012b), tomato (Li et al. 2017), and petunia (Park and Faust 2021) plants; this was expected because N is a key component of chlorophyll.

Interestingly, SPAD index and chlorophyll concentration were generally higher during the fruiting phase in plants that received 0/150 mg·L⁻¹ N compared to those treated with 50/50 mg·L⁻¹ N, suggesting that the greenness of plants can change when fertilizer is applied during postproduction (Table 2). It is plausible that these differences were related to the different substrate formulation used for plants that received 0/150 mg·L⁻¹ N.

However, in Expt. 1, tomato plants that received $\geq 50/100$ mg·L⁻¹ N had similar SPAD index values (range, 42 to 49). Similarly, tomato plants in Expt. 2 that received 0/150 or 50/50 mg·L⁻¹ N had lower chlorophyll concentrations than those treated with 50/150, 100/150, 150/150, or 200/200 mg·L⁻¹ N. For pepper, the SPAD index in Expt. 1 was more than three-times lower in plants that received 50/50 mg·L⁻¹ N compared with that of plants in all other treatments, which had similar values ranging from 47 to 53. The chlorophyll concentration in Expt. 2 was also lowest in pepper plants that received 50/50 mg·L⁻¹ N, followed by that of those treated with 100/100 mg·L⁻¹ N.

Both SPAD index and chlorophyll concentration are typically used in bedding plant production research as indicators of plant esthetic quality because of their association with plant greenness (Ferrante et al. 2015; Wang et al. 2005; Zhang et al. 2022). Although both pale green and dark green plants are acceptable to consumers (Berghage and Wolnick 2000), pale greenness caused by nutritional deficiencies is likely to affect postproduction performance, which can negatively affect consumer satisfaction (Heidari and Mohammad 2012; Pandey and Sinha 2009). Although pepper plants that received 0 mg·L⁻¹ N during the production phase were visually chlorotic and likely unmarketable, tomato plants under the same treatment were relatively green (data not shown). These observations were consistent with those of Carlson et al. (2020), who also described a lack of chlorosis in tomato plants grown without additional fertilizer for 4 weeks (other than the fertilizer starter charge already included in the substrate). The authors suggested that withholding fertilizer application during the initial weeks of production can help growers produce short, high-quality tomato plants when using substrates with fertilizer starter charge (Carlson et al. 2020). As recommended by others, applying fertilizer immediately before the end of production can be used as a strategy to increase the postproduction quality of vigorous bedding plants (Ebba et al. 2021; Park and Faust 2021). However, further studies are needed to evaluate end-of-production fertilization strategies for vegetable bedding plants that can continue to support growth, quality, and fruit set in the consumer environment.

During the production phase, the leachate EC of both species tended to increase with increasing N concentration, whereas the leachate pH generally followed the opposite trend (Table 1). Although saucers were used in these experiments to ensure that fertilizer solutions would be reabsorbed by plants, which effectively created a zero-leaching fraction that tended to increase EC (Yelanich and Biernbaum 1993), plants that received 0, 50, or 100 mg·L⁻¹ N had a leachate EC within the recommended range of production for bedding plants (1.0–2.6 mS·cm⁻¹) (Torres et al. 2010). However, the EC was higher than optimal in tomato plants in Expt. 1 treated with 150 or 200 mg·L⁻¹ N and in pepper plants in Expt. 2 treated with 200 mg·L⁻¹ N.

During the fruiting phase, the leachate EC of both species increased as the N concentration increased in the fertilizer solution but, in general, the values of plants treated with 0/150, 50/150, 100/150, or 150/150 mg·L⁻¹ N were within the recommended range of 2.7 to 4.8 mS·cm⁻¹ for established plants (Cavins et al. 2008; Torres et al. 2010) (Table 2). In Expt. 1, the leachate EC was lowest in tomato that received 50/50 mg·L⁻¹ N (1.5 mS·cm⁻¹) and highest in those treated with 200/200 mg·L⁻¹ N (6.7 mS·cm⁻¹). However, the leachate EC in tomato treated with 0/150 mg·L⁻¹ N was approximately twice that measured in plants grown with 50/50 mg·L⁻¹ N (3.1 vs. 1.5 mS·cm⁻¹, respectively). Similarly, the leachate EC in pepper plants that received 50/50 mg·L⁻¹ N in Expt. 1 was only 16% of that measured in plants treated with 200/200 mg·L⁻¹ N. In Expt. 2, the leachate EC was lowest in plants from both species that received 50/50 mg·L⁻¹ N and highest in those treated with 100/150, 150/150, or 200/200 mg·L⁻¹ N. Although the leachate EC was higher than optimal in plants treated with 200/200 mg·L⁻¹ N, no visual signs of salinity stress were evident, suggesting that, up to a point, these plants can tolerate values outside of recommended ranges. However, considering the need to minimize production costs, ECs that are higher than optimal should be avoided to minimize fertilizer waste. Providing less frequent fertilizer applications than those used in our study (e.g., once per week) may help growers maintain leachate EC closer to recommended values. In

addition, it is plausible that using irrigation practices that enable leaching will result in lower EC values than those reported here.

Except for tomato in Expt. 2 and pepper plants treated with 0 mg·L⁻¹ N, the leachate pH was within the recommended range of production for these compact vegetable plants (5.3–5.8) (Leth 2022) (Table 1). During the fruiting phase, the leachate pH tended to decrease as the N concentration increased but, in general, values in Expt. 1 were within the recommended range of 5.4 to 6.2 (Torres et al. 2010), except for those of plants treated with 200/200 mg·L⁻¹ N (Table 2). However, the leachate pH in Expt. 2 was consistently above the recommended range, which was likely attributed to the high alkalinity in the irrigation water. This also explains the general similarities in pH among treatments. Nonetheless, no visual signs suggested negative pH effects on growth, quality, or yield, likely because of the relatively short crop cycle of the plants evaluated in our study.

FRUIT YIELD. The decreasing N concentration in the fertilizer solution generally resulted in a lower fruit yield

per plant (Table 3). During both experiments, tomato plants that received 0/150 mg·L⁻¹ N produced fewer mature fruit than those treated with 200/200 mg·L⁻¹ N, and the number of fruit harvested per plant was also lower with decreasing N. For example, tomato plants that received 0/150 in Expt. 1 produced 54 fruit, which was almost half the number of mature fruit harvested from those treated with ≥100/100 mg·L⁻¹ N. Similarly, in both experiments, the mature fruit FW was lowest in tomato plants that received 0/150 mg·L⁻¹ N, but the highest values were measured in plants treated with 100/100 mg·L⁻¹ N in Expt. 1 (754 g) or 150/150 mg·L⁻¹ N in Expt. 2 (638 g). The number and FW of mature pepper fruit also decreased with decreasing N concentration in both experiments. For example, plants in Expt. 1 that received 50/50 mg·L⁻¹ N only produced 16% of the fruit and 17% of the fruit FW compared to those treated with 200/200 mg·L⁻¹ N. Correspondingly, the mature fruit FW of pepper were lowest in plants that received 50/50 mg·L⁻¹ N, followed by those treated with 50/100 mg·L⁻¹ N (57 g and 102 g, respectively). In Expt. 2,

Table 3. Mature fruit yield of ‘Siam’ tomato and ‘Basket of fire’ pepper plants grown in a greenhouse for 15 and 19 weeks, respectively, using different fertilizer treatments in two experiments.

Nitrogen concn (mg·L ⁻¹)	Mature fruit per plant			
	Total count (no.)		Total fresh wt (g)	
	1 ⁱ	2	1	2
Tomato				
0/150 ⁱⁱ	54.1 e ⁱⁱⁱ	53.9 d	412.5 e	422.1 d
50/50	64.0 de	70.5 c	493.3 d	464.5 cd
50/100	75.0 cd	75.4 bc	594.4 c	524.1 bc
50/150	78.8 bc	84.1 abc	573.3 cd	549.5 abc
100/100	97.7 a	81.9 abc	754.4 a	566.6 ab
100/150	92.8 ab	78.3 abc	691.7 ab	592.8 ab
150/150	99.8 a	86.5 ab	688.9 ab	637.5 a
200/200	101.0 a	91.3 a	631.4 bc	614.9 ab
Pepper				
0/150	—	289.0 d	—	117.7 d
50/50	62.3 g	176.5 e	56.8 g	87.5 e
50/100	109.2 fg	392.3 c	101.8 fg	146.9 cd
50/150	145.5 ef	484.6 b	119.8 ef	202.9 b
100/100	192.7 de	418.4 bc	162.7 de	132.1 d
100/150	253.2 cd	471.6 bc	202.4 cd	182.0 bc
150/150	325.7 b	731.6 a	277.0 b	277.2 a
200/200	396.3 a	767.0 a	332.7 a	286.6 a

ⁱ Experiment number, where 1 = fertilizer treatments applied with every irrigation event in Gainesville, FL, USA, and 2 = fertilizer treatments applied every other irrigation event in West Lafayette, IN, USA.

ⁱⁱ Numbers represent the concentrations used during the production and fruiting phases, respectively.

ⁱⁱⁱ For each species, means within column followed by the same letter are not different based on Tukey's honestly significant difference test at $P \leq 0.05$.

pepper plants that received 150/150 or 200/200 mg·L⁻¹ N produced more mature fruit than those in all other treatments, and those treated with 50/50 mg·L⁻¹ N produced the smallest number of fruit and had the lowest fruit FW (88 g). Mature fruit FW was also lower in pepper plants that received 0/150 or 100/100 mg·L⁻¹ N compared with those treated with 50/150 or 100/150 mg·L⁻¹ N.

Our results correspond with the findings of others who have shown a lower fruit yield in response to decreasing N concentrations for both tomato and pepper plants (Ayodele et al. 2015; Cheng et al. 2021). When evaluating the fertilizer concentration for tomato production in the field, Ronga et al. (2020) reported 22% lower fruit FW when the N concentration decreased from 200 to 0 mg·L⁻¹, but yield was only 6% lower when the N concentration decreased from 50 to 0 mg·L⁻¹. Aminifard et al. (2012b) also found that as the N concentration decreased from 150, 100, or 50 to 0 mg·L⁻¹, the fruit FW of pepper plants grown in the field decreased by 11%, 27%, or 15%, respectively. For greenhouse-grown tomato plants, Wang and Xing (2016) reported that reducing the N concentration from 150 to 75 mg·L⁻¹ resulted in 28% lower fruit FW. Similarly, Grasso et al. (2022) found that decreasing the N concentration from approximately 252 to 36 mg·L⁻¹ during greenhouse production of pepper plants resulted in 59% lower fruit FW. Overall, our findings showed that the N concentration during production will impact yield during postproduction.

Surprisingly, there were no treatment differences for the Brix of tomato fruit, with values ranging from 3.2 to 3.8 °Brix in the two experiments (data not shown). Our results were similar to those of others who have reported minimal effects on the sugar content of tomato fruit when comparing different N concentrations (Di Cesare et al. 2010; Ronga et al. 2020). However, some studies have shown that increasing EC in the fertilizer solution can help increase the sugar content in greenhouse-grown tomatoes (Kubota et al. 2012; Saito et al. 2008). Because the sugar content in tomato fruit can be influenced by a variety of factors, including fruit size and overall plant yield (Klann et al. 1996), it is plausible that our findings are attributed to the limited yield of

the compact plants used in our study, which were determinate cultivars with genetically defined yield potential. In contrast, studies that reported the positive effects of high EC in tomato fruit have used indeterminate cultivars for commercial production, which tend to produce significantly higher yields for extended periods of time.

INTUMESCENCE IN PEPPER PLANTS.

Intumescence is a cultivar-specific physiological disorder that causes tumor-like lesions on the surface of susceptible plants (Williams et al. 2016). This disorder has been widely documented in tomato, but only a few studies have reported injury on pepper plants (Cruz et al. 2023; Massa et al. 2008; Savvas et al. 2008). Although intumescence may not always affect growth or yield, it can reduce the esthetic quality of plants, which is a significant problem during vegetable bedding plant production. In both experiments, the intumescence severity and incidence tended to increase in pepper plants treated with higher N concentrations, suggesting that fertilizer application affects development of the disorder (Table 4). However, both variables were differently affected during the two experiments.

During the production phase in Expt. 1, the incidence on the upper leaf surface increased from 1% to 86% as the N concentration increased from 50 to 200 mg·L⁻¹, but no intumescence was measured on the lower leaf surface (Table 4). Additionally, severity was highest in plants that received 200 mg·L⁻¹ N (3.1), but it was similarly low in plants from all other treatments (range, 0.0 to 0.5). In Expt. 2, there was no intumescence on the upper leaf surface of plants during the production phase, but both the incidence and severity on the lower leaf surface tended to increase as the N concentration increased from 0 to 200 mg·L⁻¹ N. During the fruiting phase, plants in Expt. 1 that received 50/50 mg·L⁻¹ N had no intumescence on either leaf side, and those treated with 100/100 mg·L⁻¹ N had a lower incidence (11%) on the upper leaf surface compared to plants treated with 50/150, 150/150, or 200/200 mg·L⁻¹ N (40%, 43%, or 64%, respectively). The incidence on the lower leaf surface was highest in pepper plants that received 200/200 mg·L⁻¹ N (60%), but it was similar among those in all other treatments. Furthermore, intumescence severity was

generally low during the fruiting phase, but scores were generally higher in plants treated with 200/200 mg·L⁻¹ N. During the fruiting phase in Expt. 2, the incidence on the upper leaf surface generally increased as N increased. For example, the incidence of plants treated with 50/50 mg·L⁻¹ N was only 24%, whereas that of plants that received 200/200 mg·L⁻¹ N was 87%. However, the incidence on the lower leaf surface was lowest in plants treated with 50/50 or 100/100 mg·L⁻¹ N, but it was similarly high in plants from all other treatments (range, 81% to 100%). Intumescence severity on both leaf surfaces of plants in Expt. 2 was highest under 200/200 mg·L⁻¹ N, followed by that of those that received 150/150 mg·L⁻¹ N. The severity of plants treated with 0/150 mg·L⁻¹ N was lowest on the upper leaf surface, but it was the third highest on the lower leaf surface.

Studies have shown that Ca can affect intumescence development in plants like potato (*Solanum tuberosum*) (Schabow and Palta 2019), cuphea (*Cuphea lysopifolia*) (Craver et al. 2014), sweetpotato (*Ipomoea batatas*) (Craver et al. 2014), and tomato (Sita et al. 2023). To our knowledge, this is the first study to show differences in intumescence in response to the N concentration. The mechanisms that affect the development of the disorder remain unclear; however, Suarez et al. (2023) postulated that plants affected by intumescence accumulate calcium oxalate crystals, which limit the availability of Ca for proper cell wall structure and tissue development. Because N can promote oxalate biosynthesis (Xing et al. 2024), it is plausible that increasing N in the fertilizer solution further increases the accumulation of calcium oxalate crystals in susceptible plants, thus making them more prone to developing intumescence injury.

The different greenhouse glazing materials and their corresponding transmission of ultraviolet radiation are likely responsible for the variation in intumescence response measured in our two experiments. As shown by others, a lack of ultraviolet radiation in controlled environments is a common cause of intumescence development (Craver et al. 2014; Eguchi et al. 2016; Kubota et al. 2017). The greenhouse used in Expt. 1 had polycarbonate glazing, which has ultraviolet transmission values ranging from approximately 20% to 50% (Both

Table 4. Intumescence incidence and severity of ‘Basket of Fire’ pepper plants grown in a greenhouse after 9 (production phase) or 19 (fruiting phase) weeks using different fertilizer treatments in two experiments.

Nitrogen concn (mg·L ⁻¹)	Upper incidence (%) ^{i,ii}		Lower incidence (%)		Upper severity (1–10) ⁱⁱⁱ		Lower severity (1–10)	
	1 ^{iv}	2	1	2	1	2	1	2
Production phase								
0	—	—	—	7 d	—	—	—	0.5 c
50	1 c ^{vi}	—	—	43 b	0.0 b	—	—	1.2 c
100	16 bc	—	—	63 ab	0.4 b	—	—	3.2 b
150	25 b	—	—	66 ab	0.5 b	—	—	5.4 a
200	86 a	—	—	73 a	3.1 a	—	—	4.6 a
Fruiting phase								
0/150 ^v	—	33 de	—	91 a	—	1.5 e	—	5.5 bc
50/50	0 c	24 e	0 c	50 b	0.0 c	1.4 e	0.0 c	2.1 d
50/100	24 bcd	46 bcd	30 b	83 a	0.5 bc	3.0 cd	0.1 bc	4.5 c
50/150	40 ab	43 cd	50 b	86 a	0.8 b	3.7 c	0.4 abc	4.4 c
100/100	11 cd	48 bc	50 b	52 b	0.5 bc	2.3 d	0.1 bc	4.1 c
100/150	31 bc	58 b	50 b	81 a	0.7 b	2.7 d	0.4 abc	4.6 c
150/150	43 ab	82 a	50 b	83 a	0.7 b	5.6 b	0.5 ab	6.8 b
200/200	64 a	87 a	60 a	100 a	1.7 a	7.0 a	0.7 a	8.5 a

ⁱ Incidence was calculated by counting the number of leaves with intumescence and dividing that number by the total number of leaves counted on a main branch.

ⁱⁱ Upper and lower refer to the leaf surface evaluated.

ⁱⁱⁱ Severity score whereby the percentage indicates the leaf area covered by intumescence: 0 = no intumescence; 1 = 1% to 10%; 2 = 11% to 20%; 3 = 21% to 30%; 4 = 31% to 40%; 5 = 41% to 50%; 6 = 51% to 60%; 7 = 61% to 70%; 8 = 71% to 80%; 9 = 81% to 90%; and 10 = 91% to 100%.

^{iv} Experiment number, where 1 = fertilizer treatments applied with every irrigation event in Gainesville, FL, USA, and 2 = fertilizer treatments applied every other irrigation event in West Lafayette, IN, USA.

^v Numbers represent the concentrations used during the production and fruiting phases, respectively.

^{vi} Within phase, the means within the column followed by the same letter are not different based on Tukey’s honestly significant difference test at $P \leq 0.05$.

2002). In contrast, plants in Expt. 2 were grown in a glass-glazed greenhouse with ultraviolet transmission of approximately 70% (Both 2002; Runkle 2020). Furthermore, Expt. 1 was located in Florida, which has a higher average ultraviolet index than that of Indiana, where Expt. 2 was performed (US Environmental Protection Agency 2024). Our findings correspond with those of others who showed that the growing environment plays a crucial role during intumescence development and demonstrated that N concentration in the fertilizer solution can affect both the incidence and severity of the disorder in pepper plants.

Conclusion

Growth and yield followed similar trends between the two experiments and generally showed that tomato and pepper plants that received a lower N concentration during both production and fruiting phases tended to be shorter, had a smaller GI, and produced a lower fruit yield than those treated with higher N. Plant greenness, measured as either SPAD index or chlorophyll concentration,

was generally lower in plants that received a lower N concentration during the production phases and maintained a similar pattern in the fruiting phases. However, at the end of both experiments, the greenness of plants that received 0/150 mg·L⁻¹ N tended to be higher than that of those treated with 50/50 mg·L⁻¹ N, suggesting that providing a higher N during postproduction can help improve quality when lower N concentrations are used during production. Fruit yield was generally lowest in plants from both species treated with either 0/150 or 50/50 mg·L⁻¹ N; in general, tomato plants treated with $\geq 100/100$ mg·L⁻¹ N had a similar fruit yield. However, the yield of pepper plants tended to increase with higher N concentration during both the production and fruiting phases. Intumescence of pepper plants also increased with higher N concentration, but there were different responses between the two experiments, suggesting that the growing environment plays a role during development of the disorder. Overall, our findings showed that reducing the initial N concentration during production

has the potential to help greenhouse growers produce smaller vegetable bedding plants but also negatively affects growth, quality, and yield during the postproduction and fruiting phases.

References cited

- Ågren G, Wetterstedt JÅ, Billberger MF. 2012. Nutrient limitation on terrestrial plant growth-modeling the interaction between nitrogen and phosphorous. *New Phytol.* 194(4):953–960. <https://doi.org/10.1111/j.1469-8137.2012.04116.x>.
- Alem P, Thomas PA, van Iersel MW. 2015. Controlled water deficit as an alternative to plant growth retardants for regulation of poinsettia stem elongation. *HortScience.* 50(4):565–569. <https://doi.org/10.21273/HORTSCI.50.4.565>.
- Aminifard MH, Aroice H, Nemati H, Azizi M, Khayyat M. 2012a. Effect of nitrogen fertilizer on vegetative and reproductive growth of pepper plants under field conditions. *J Plant Nutr.* 35(2):235–242. <https://doi.org/10.1080/01904167.2012.636126>.
- Aminifard MH, Aroice H, Ameri A, Fatemi H. 2012b. Effect of plant density and nitrogen fertilizer on growth, yield and fruit quality of sweet pepper (*Capsicum annuum* L.). *Afr J Agric Res.* 7:859–866. <https://doi.org/10.5897/AJAR10.505>.
- Amsen M, Nielsen OF. 1991. Negative DIF: Mean room temperature control and its effect on environment and energy consumption. *DIPS.* 2173:433–439. https://dcapub.au.dk/pub/planteavl_95_433.pdf.
- Ayodele OJ, Alabi EO, Aluko M. 2015. Nitrogen fertilizer effects on growth, yield and chemical composition of hot pepper (rodo). *Int J Agri Crop Sci.* 8:666–673.
- Berghage RD, Wolnick DJ. 2000. Consumer color preference in new guinea impatiens. *HortTechnology.* 10(1):206–208. <https://doi.org/10.21273/HORTTECH.10.1.206>.
- Bergstrand KJ. 2022. Organic fertilizers in greenhouse production systems - a review. *Sci Hortic.* 295:110855. <https://doi.org/10.1016/j.scienta.2021.110855>.
- Boldt JK. 2018. Short-term reductions in irradiance and temperature minimally affect growth and development of five floriculture species. *HortScience.* 53(1):33–37. <https://doi.org/10.21273/HORTSCI10289-17>.
- Both AJ. 2002. Greenhouse glazing. *Horticultural Engineering Newsletter.* Rutgers NJAES. 17:5–6. <http://horteng.envsci.rutgers.edu/newsletter/2002/vol17-1jan2002.pdf>. [accessed 2 Mar 2024].

- Bridgen MP. 2016. Using ultraviolet-C (UV-C) irradiation on greenhouse ornamental plants for growth regulation. *Acta Hortic.* 1134:49–56. <https://doi.org/10.17660/ActaHortic.2016.1134.7>.
- Cavins TJ, Whipker BE, Fonteno WC. 2008. PourThru: A method for monitoring nutrition in the greenhouse. *Acta Hortic.* 779:289–298. <https://doi.org/10.17660/ActaHortic.2008.779.35>.
- Carlson A, Guo Y, Bogard J. 2020. Vegetable fertility basics for flower growers. <https://www.growertalks.com/Article/?articleid=24866>. [accessed 17 Jan 2024].
- Caspersen S, Bergstrand KJ. 2020. Phosphorus restriction influences P efficiency and ornamental quality of poinsettia and chrysanthemum. *Sci Hortic.* 267:109316. <https://doi.org/10.1016/j.scienta.2020.109316>.
- Cheng M, Wang H, Fan J, Xiang Y, Tang S, Pei S, Zeng H, Zhang C, Dai Y, Li Z, Zou Y, Zhang F. 2021. Effects of nitrogen supply on tomato yield, water use efficiency and fruit quality: A global meta-analysis. *Sci Hortic.* 290:110553. <https://doi.org/10.1016/j.scienta.2021.110553>.
- Craver JK, Miller CT, Williams KA, Bello NM. 2014. Ultraviolet radiation affects intumescence development in ornamental sweetpotato (*Ipomoea batatas*). *HortScience.* 49(10):1277–1283. <https://doi.org/10.21273/HORTSCI.49.10.1277>.
- Cruz S, Gómez C. 2022. Effects of daily light integral on compact tomato plants grown for indoor gardening. *Agronomy.* 12(7):1704. <https://doi.org/10.3390/agronomy12071704>.
- Cruz S, van Santen E, Gómez C. 2023. Evaluation of compact pepper cultivars for container gardening indoors under light-emitting diodes and in a greenhouse under sunlight. *HortTechnology.* 33(3):317–324. <https://doi.org/10.21273/HORTTECH05194-23>.
- Cruz S, van Santen E, Gómez C. 2022. Evaluation of compact tomato cultivars for container gardening indoors and under sunlight. *Horticulturae.* 8(4):294. <https://doi.org/10.3390/horticulturae8040294>.
- Currey CJ, Flax NJ, Litvin AG, Metz VC. 2019. Substrate volumetric water content controls growth and development of containerized culinary herbs. *Agronomy.* 9(11):667. <https://doi.org/10.3390/agronomy9110667>.
- Currey CJ, Metz VC, Flax NJ, Litvin AG, Whipker BE. 2020. Restricting phosphorus can manage growth and development of containerized sweet basil, dill, parsley, and sage. *HortScience.* 55(11):1722–1729. <https://doi.org/10.21273/HORTSCI14882-20>.
- Di Cesare LF, Migliori C, Viscardi D, Parisi M. 2010. Quality of tomato fertilized with nitrogen and phosphorous. *Ital J Food Sci.* 22:186–191.
- Dufault RJ. 1998. Vegetable transplant nutrition. *HortTechnology.* 8(4):515–523. <https://doi.org/10.21273/HORTTECH.8.4.515>.
- Dunn BL, Goad C, Brandenberger L. 2022. Growth and flowering of greenhouse-grown tomato transplants in response to uniconazole. *HortTechnology.* 32(6):485–490. <https://doi.org/10.21273/HORTTECH05071-22>.
- Ebba J, Dickson RW, Fisher PR, Harris CN, Guerdat T, Flores S. 2021. Fertilizer and plant growth regulator strategies for improving consumer performance of container-grown petunia. *HortTechnology.* 31(3):304–314. <https://doi.org/10.21273/HORTTECH04757-20>.
- Eguchi T, Hernández R, Kubota C. 2016. Far-red and blue light synergistically mitigate intumescence injury of tomato plants grown under ultraviolet-deficit light environment. *HortScience.* 51(6):712–719. <https://doi.org/10.21273/HORTSCI.51.6.712>.
- Etissa E, Dechassa N, Alamirew T, Alemayehu Y, Desalegn L. 2013. Growth and yield components of tomato as influenced by nitrogen and phosphorus fertilizer applications in different growing seasons. *Ethiop J Agri Sci.* 23:57–77. <https://www.ajol.info/index.php/ejas/article/view/142855>.
- Feng L, Raza MA, Li Z, Chen Y, Bin Khalid MH, Du J, Liu W, Wu X, Song C, Yu L, Zhang Z, Yuan S, Yang W, Yang F. 2019. The influence of light intensity and leaf movement on photosynthesis characteristics and carbon balance of soybean. *Front Plant Sci.* 9:1952. <https://doi.org/10.3389/fpls.2018.01952>.
- Ferrante A, Trivellini A, Scuderi D, Romano D, Vernieri P. 2015. Post-production physiology and handling of ornamental potted plants. *Postharvest Biol Technol.* 100:99–108. <https://doi.org/10.1016/j.postharvbio.2014.09.005>.
- Fisher P. 2013. The 1 to 5 plug gray moisture scale. https://www.spring-lake.net/pdfs/gh-tech/Plug_Tray_Moisture_Scale.pdf. [accessed 25 Aug 2022].
- Gao F, Li H, Mu X, Gao H, Zhang Y, Li R, Cao K, Ye L. 2023. Effects of organic fertilizer application on tomato yield and quality: A meta-analysis. *Appl Sci.* 13(4):2184. <https://doi.org/10.3390/app13042184>.
- Grasso R, Peña-Fleitas MT, de Souza R, Rodríguez A, Thompson RB, Gallardo M, Padilla FM. 2022. Nitrogen effect on fruit quality and yield of muskmelon and sweet pepper cultivars. *Agronomy.* 12(9):2230. <https://doi.org/10.3390/agronomy12092230>.
- Harp D, Pulat S. 2008. Nitrogen level affects greenhouse growth and quality of ornamental white clover (*Trifolium repens* L.). *Sub Plant Sci.* 60:8–12.
- Heidari M, Mohammad MM. 2012. Effect of rate and time of nitrogen application on fruit yield and accumulation of nutrient elements in *Momordica charantia*. *J Saudi Soc Agric Sci.* 11(2):129–133. <https://doi.org/10.1016/j.jssas.2012.02.003>.
- Jardin P. 2015. Plant biostimulants: Definition, concept, main categories and regulation. *Sci Hortic.* 196:3–14. <https://doi.org/10.1016/j.scienta.2015.09.021>.
- Kang J, van Iersel MW. 2009. Managing fertilization of bedding plants: A comparison of constant fertilizer concentrations versus constant leachate electrical conductivity. *HortScience.* 44(1):151–156. <https://doi.org/10.21273/HORTSCI.44.1.151>.
- Karlsson MG, Heins RD, Erwin JE, Berghage RD, Carlson WH, Biernbaum JA. 1989. Temperature and photosynthetic photon flux influence chrysanthemum shoot development and flower initiation under short-day conditions. *J Am Soc Hortic Sci.* 114(1):158–163. <https://doi.org/10.21273/JASHS.114.1.158>.
- Kendal D, Williams K, Williams N. 2012. Plant traits link people's plant preferences to the composition of their gardens. *Landsc Urban Plan.* 105(1–2):34–42. <https://doi.org/10.1016/j.landurbplan.2011.11.023>.
- Klann EM, Hall B, Bennett AB. 1996. Antisense acid invertase (TW7) gene alters soluble sugar composition and size in transgenic tomato fruit. *Plant Physiol.* 112(3):1321–1330. <https://doi.org/10.1104/pp.112.3.1321>.
- Kubota C, Kroggel M, Torabi M, Dietrich KA, Kim H, Fonseca J, Thomson CA. 2012. Changes in selected quality attributes of greenhouse tomato fruit as affected by pre- and postharvest environmental conditions in year-round production. *HortScience.* 47(12):1698–1704. <https://doi.org/10.21273/HORTSCI.47.12.1698>.
- Kubota C, Eguchi T, Kroggel M. 2017. UV-B radiation dose requirement for suppressing intumescence injury on tomato plants. *Sci Hortic.* 226:366–371. <https://doi.org/10.1016/j.scienta.2017.09.006>.
- Latimer JG. 1998. Mechanical conditioning to control height. *HortTechnology.* 8(4):529–534. <https://doi.org/10.21273/HORTTECH.8.4.529>.

- Latimer JG, Oetting R. 1998. Greenhouse conditioning affects landscape performance of bedding plants. *J Environ Hortic.* 16(3):138–142. <https://doi.org/10.24266/0738-2898-16.3.138>.
- Lebude A, Bilderback T. 2009. The pour-through extraction procedure: A nutrient management tool for nursery crops. North Carolina State University Cooperative Extension. <https://content.ces.ncsu.edu/the-pour-through-extraction-procedure-a-nutrient-management-tool-for-nursery-crops>. [accessed 12 Sep 2022].
- Leth C. 2022. Kitchen minis tabletop vegetables: A growing guide. <https://www.growertalks.com/Article/?articleid=25940>. [accessed 16 Jan 2024].
- Littlefield S. 2023. The top five home-grown vegetables. The National Gardening Association. <https://garden.org/learn/articles/view/3850/The-Top-Five-Home-grown-Vegetables/>. [accessed 23 Jan 2024].
- Litvin AG, van Iersel MW, Malladi A. 2016. Drought stress reduces stem elongation and alters gibberellin-related gene expression during vegetative growth of tomato. *J Am Soc Hortic Sci.* 141(6):591–597. <https://doi.org/10.21273/JASHS03913-16>.
- Liu J, Leatherwood W, Mattson NS. 2012. Irrigation method and fertilizer concentration differentially alter growth of vegetable transplants. *HortTechnology.* 22(1):56–63. <https://doi.org/10.21273/HORTTECH.22.1.56>.
- Li Y, Sun Y, Liao S, Zou G, Zhao T, Chen Y, Yang J, Zhang L. 2017. Effects of two slow-release nitrogen fertilizers and irrigation on yield, quality, and water-fertilizer productivity of greenhouse tomato. *Agric Water Manag.* 186:139–146. <https://doi.org/10.1016/j.agwat.2017.02.006>.
- Massa GD, Kim H, Wheeler RM, Mitchell CA. 2008. Plant productivity in response to LED lighting. *HortScience.* 43(7):1951–1956. <https://doi.org/10.21273/HORTSCI.43.7.1951>.
- Nemali K, van Iersel M. 2004. Light intensity and fertilizer concentration: I. estimating optimal fertilizer concentrations from water-use efficiency of wax begonia. *HortScience.* 39(6):1287–1292. <https://doi.org/10.21273/HORTSCI.39.6.1287>.
- Pandey SN, Sinha BK. 2009. *Plant Physiology* (4th ed). Vikas Publishing House Private Ltd, New Delhi, India.
- Park J, Faust JE. 2021. Fertilization strategy affects production and postproduction performance of petunia. *HortTechnology.* 31(2):217–224. <https://doi.org/10.21273/HORTTECH04764-20>.
- Park J, Faust JE. 2023. Fertilization and paclobutrazol application for sustainable production and post-production performance of petunia. *HortTechnology.* 33(2):225–232. <https://doi.org/10.21273/HORTTECH05086-22>.
- Prasad H, Sajwan P, Kumari M, Solanki S. 2016. Effect of organic manures and biofertilizer on plant growth, yield and quality of horticultural crop: A review. *Int J Chem Stud.* 5:217–221.
- Rajakapse NC, Kelly JW. 1992. Regulation of chrysanthemum growth by spectral filters. *J Am Soc Hortic Sci.* 117(3):481–485. <https://doi.org/10.21273/JASHS.117.3.481>.
- Richardson M, Arlotta C. 2022. Producing cherry tomatoes in urban agriculture. *Horticulturae.* 8(4):274–284. <https://doi.org/10.3390/horticulturae8040274>.
- Ronga D, Pentangelo A, Parisi M. 2020. Optimizing N fertilization to improve yield, technological and nutritional quality of tomato grown in high fertility soil conditions. *Plants.* 9(5):575. <https://doi.org/10.3390/plants9050575>.
- Runkle E. 2009. ABA coming to floriculture. Michigan State University Extension Floriculture Team. <https://www.canr.msu.edu/uploads/resources/pdfs/abacomingtofloriculture.pdf>. [accessed 12 Feb 2024].
- Runkle E. 2020. Greenhouse Product News. UV-Transmitting greenhouse glazing. <https://gpnmag.com/article/uv-transmitting-greenhouse-glazing/>. [accessed 3 Mar 2024].
- Saito T, Fukuda N, Iikubo T, Inai S, Fujii T, Konishi C, Ezura H. 2008. Effects of root-volume restriction and salinity on the fruit yield and quality of processing tomato. *J Japan Soc Hort Sci.* 77(2):165–172. <https://doi.org/10.2503/jjshs1.77.165>.
- Savvas D, Ntatsi G, Passam HC. 2008. Plant nutrition and physiological disorders in greenhouse-grown tomato, pepper, and eggplant. *Eur J Plant Sci Biotechnol.* 2:45–61.
- Schabow J, Palta J. 2019. Intumescence injury in the leaves of russet burbank potato plants is mitigated by calcium nutrition. *Am J Potato Res.* 96(1):6–12. <https://doi.org/10.1007/s12230-018-9682-9>.
- Sita CN, Kousaka A, Tamoi A, Ozawa R, Iriawati C, Kiriya Y, Suzuki K. 2023. Incidence of intumescence injury in several tomato cultivars under different calcium conditions. *J Japan Soc Hort Sci.* 92(4):476–484. <https://doi.org/10.2503/hortj.QH-072>.
- Suarez E, Agrawal P, Izzo LG, Gómez C. 2023. intumescence response by tomato plants grown in a greenhouse or indoors using two types of soilless culture systems. *HortScience.* 58(12):1550–1559. <https://doi.org/10.21273/HORTSCI17415-23>.
- Torres A, Mickelbart M, Lopez RG. 2010. Measuring pH and EC of large container crops. *Greenhouse Product News.* <https://gpnmag.com/article/measuring-ph-and-ec-large-container-crops/>. [accessed 10 Oct 2024].
- US Environmental Protection Agency. 2024. Sun safety monthly average UV index 2006–2023. <https://www.epa.gov/sunsafety/sun-safety-monthly-average-uv-index-2006-2023>. [accessed 3 Mar 2024].
- van Iersel M. 1997. Root restriction effects on growth and development of salvia (*Salvia splendens*). *HortScience.* 32(7):1186–1190. <https://doi.org/10.21273/HORTSCI.32.7.1186>.
- Wang Q, Chen J, Stamps RH, Li Y. 2005. Correlation of visual quality grading and SPAD reading of green-leaved foliage plants. *J Plant Nutr.* 28(7):1215–1225. <https://doi.org/10.1081/PLN-200063255>.
- Wang X, Xing Y. 2016. Effects of irrigation and nitrogen fertilizer input levels on soil -N content and vertical distribution in greenhouse tomato (*Lycopersicon esculentum* Mill.). *Scientifica.* 2016:5710915. <https://doi.org/10.1155/2016/5710915>.
- Whipker BE, McCall I, Buhler W, Krug B. 2011. Flurprimidol preplant soaks and substrate drenches control excessive growth of forced bulbs. *Acta Hortic.* 886:385–391. <https://doi.org/10.17660/ActaHortic.2011.886.53>.
- White S, Scoggins H. 2005. Fertilizer concentration affects growth response and leaf color of *Tradescantia virginiana* L. *J Plant Nutr.* 28(10):1767–1783. <https://doi.org/10.1080/01904160500250896>.
- Williams KA, Miller CT, Craver JK. 2016. Light quality effects on intumescence (oedema) on plant leaves, p 275–286. In: Kozai T, Fujiwara K, Runkle ES (eds). *LED lighting for urban agriculture*. Springer, Singapore. <https://doi.org/10.1007/978-981-10-1848-0>.
- Xing Y, Feng Z-Q, Zhang X, Cao H-X, Liu C-L, Qin H-H, Jiang H, Zhu Z-L, Ge S-F, Jiang Y-M. 2024. Nitrogen reduces calcium availability by promoting oxalate biosynthesis in apple leaves. *Hortic Res.* 11(10):uhac208. <https://doi.org/10.1093/hr/uhac208>.
- Yelanich MV, Biernbaum JA. 1993. Root-medium nutrient concentration and growth of poinsettia at three fertilizer concentrations and four leaching fractions. *J Am Soc Hortic Sci.* 118(6):771–776. <https://doi.org/10.21273/JASHS.118.6.771>.
- Zhang R, Yang P, Liu S, Wang C, Liu J. 2022. Evaluation of the methods for estimating leaf chlorophyll content with SPAD chlorophyll meters. *Remote Sens.* 14(20):5144. <https://doi.org/10.3390/rs14205144>.