Evaluating the Effect of Fertilization and Substrate Volumetric Water Content on Compact Tomato and Pepper Plants

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KEYWORDS. *Capsicum annuum*, controlled-water deficit, dwarf, fertilizer, postproduction, *Solanum lycopersicum*

ABSTRACT. Interest in compact vegetable plants for home gardening is increasing, but the production guidelines for these new crops are limited. Our objective was to characterize the effects of fertilizer use and substrate volumetric water content (VWC) on growth, quality, and yield of compact tomato and pepper plants. During a production phase, 'Siam' tomato and 'Basket of Fire' pepper were grown in a greenhouse for 22 days and 44 days, respectively, using 4-inch containers. Plants received water-soluble fertilizer once per week or tap water only and relied on the fertilizer starter charge in the substrate (electrical conductivity = 1.0 mS·cm^{-1}). Plants were irrigated to container capacity when the substrate VWC reached 0.15, 0.30, 0.45, or 0.60 m^{3}·m^{-3}. During the postproduction phase, plants were allowed to wilt to assess the time required to reach different wilting stages or were transplanted into 8-inch containers, top-dressed with controlled-release fertilizer, and grown to harvest to evaluate carryover treatment effects. Our results showed that limiting the fertilizer application during production can have a larger effect on plant growth and yield than restricting VWC when the substrate is brought back to container capacity after each irrigation event. For example, plants of both species irrigated with only tap water during the production phase were shorter, had less biomass, and generally produced less fruit compared to plants that received fertilizer. In contrast, shoot height and shoot dry weight of tomato were the only two growth variables affected by VWC, and peppers were mostly unresponsive to differences in VWC. Although plants irrigated with only tap water during production had lower chlorophyll concentrations than those of plants that were fertilized, they quickly greened after receiving a single dose of fertilizer solution, suggesting that using a residual fertilizer strategy before shipping may help increase plant greenness when height-control treatments that induce chlorosis are used. Furthermore, wilt progression was slower in plants of both species irrigated with only tap water during the production phase, likely because of their smaller size that limited water demand. During the postproduction phase, the only differences in growth and yield were measured in pepper plants; fertilized plants were larger and produced more fruit compared to plants irrigated with only tap water during the production phase. Based on our results, growers should limit their fertilizer use when trying to produce compact vegetable plants, possibly relying only on the fertilizer starter charge incorporated into the substrate during short production cycles. However, reducing irrigation frequency may not have an effect on height and overall growth if plants are watered thoroughly each time.

New cultivars of compact fruiting vegetables have become available in recent years, thus creating a niche market opportunity for greenhouse growers who produce vegetable bedding plants for spring sale (Cruz et al. 2022, 2023; Richardson and Arlotta 2022). Among those, tomato (*Solanum lycopersicum*) and pepper (*Capsicum annuum*) tend to be the most favored among consumers in the United States (Littlefield 2023). Although these compact cultivars were bred to fit in small urban spaces, recent studies have shown that the dynamic environmental conditions in most greenhouses can greatly affect their size and shape. Cruz et al. (2022, 2023) reported differences of up to 80% in the growth index (which integrates height and width) between compact tomato and pepper plants of the same cultivar grown in two different environments, demonstrating that controlling growth during the initial stages of production is critical. However, strict regulations with the use of chemical plant growth regulators for edible crops such as vegetables and herbs require growers to use alternative methods of height control (Jardin 2015).

Although various nonchemical means of height control for ornamental plants have been evaluated (Alem et al. 2015; Bridgen 2016; Cáceres-Mella et al. 2017; Feng et al. 2019; Jacobson et al. 2015; Latimer 1998; Nemali and van Iersel 2004; Rajapakse and Kelly 1992; van Iersel et al. 2010), limited information describing the effects of some of these strategies on edible crops is available. A common industry recommendation to keep vegetable bedding plants short involves the application of mild levels of drought stress during production (Carlson et al. 2020; Leth 2022). Accordingly, controlled water deficit (CWD), which consists of restricting the irrigation frequency by continuously monitoring the substrate volumetric water content (VWC), has been shown to help regulate the height of edible crops. Litvin et al. (2016) explained that changes in the VWC when using CWD affect stem elongation through altered gibberellin acid metabolism, which regulates cell expansion and division. In a study that evaluated the effect of CWD on passion fruit (*Passiflora alata*) grown in a greenhouse, Souza et al. (2018) found that plants exposed to lower VWC were shorter and generally smaller than those under higher VWC. Similarly, in a study focused on culinary herb production, Currey et al. (2019) showed that decreasing VWC through the use of CWD helped produce shorter parsley (*Petroselinum crispum*), sage (*Salvia officinalis*), basil (*Ocimum basillicum*), and dill (*Anethum graveolens*) plants with a smaller canopy width. Although various studies have evaluated the effect of drought stress on the yield of field-grown tomato and pepper plants (Chakma et al. 2021; Delfine et al. 2001; González-Chavira et al. 2018; Lu et al. 2019; Mardani et al. 2017), no studies have described how changes in VWC during greenhouse production affect postproduction performance (i.e., fruit yield, plant growth, and esthetic quality) when these crops are grown as bedding plants.

Studies that evaluated the effect of fertilizer concentration have also shown the potential to help regulate the height of vegetable plants during greenhouse production. For example, Liu et al. (2012) found that as the nitrogen (N) concentration decreased from 350 to 50 mg·L^{-1}, the shoot height of tomato transplants decreased by 12%, but minimal effects were reported for pepper transplants. Limiting the phosphorous (P) concentration during production has also been shown to limit the shoot height of culinary herbs such as parsley, sage, basil, and dill (Currey et al. 2020). In an industry report, Carlson et al. (2020) showed that tomato plants grown without fertilizer that relied only on the fertilizer starter charge in the substrate were shorter and of higher quality than those treated with 50 or 200 $mg \cdot L^{-1}$ N once per week. However, to our knowledge, no studies have described the combined effect of limiting the substrate VWC and N concentration during the production of fruiting vegetables. Therefore, the objectives of this study were to characterize the effect of fertilizer use and VWC on the growth and plant quality of compact tomato and pepper plants during production and evaluate postproduction treatment effects on growth, quality, and yield.

Materials and methods

Two experimental runs were conducted during this study. The seed of 'Siam' tomato (PanAmerican Seed Co., Chicago, IL, USA) and 'Basket of Fire' pepper (Syngenta AG, Basel, Switzerland) were individually sown on 3 May 2023 during the first run, and on 31 Jul 2023 (tomato) and 30 Aug 2023 (pepper) during the second run. Seeds were sown into industry-standard 72-cell propagation trays (individual cell volume, 41 mL; HC Co., Boise, ID, USA) filled with horticulture-grade substrate (BM2 Seed Germination; Berger, QC, Canada). The substrate was composed of 70% (v/v) fine peatmoss, 15% (v/v) fine perlite, and 15% (v/v) fine vermiculite, and it had an electrical conductivity (EC) of 1.0 $mS \cdot cm^{-1}$ and pH of 5.6 according to the manufacturer's label. Trays were covered with cheese cloth until uniform germination occurred.

Seedling trays were placed on a metallic mesh bench [2.4 m (width) × 9.8 m (length)] inside a glass-glazed greenhouse in West Lafayette, IN, USA (lat. 40°N). The greenhouse had retractable shade curtains, pad-and-fan evaporative cooling, and mechanical heating controlled by an environmental control system (Maximizer Precision 10; Priva Computers, Vineland Station, ON, Canada). Relative humidity (RH) was measured with a datalogger (HOBO UX100-023; Onset Computer Corporation, Bourne, MA, USA), and the temperature and daily light integral (DLI) were measured with probes (107 Temperature Probe; Campbell Scientific, Inc., Logan, UT, USA) and quantum sensors (SQ-500-SS; Apogee Instruments, Inc., Logan, UT, USA), respectively, placed at above-canopy height in the center of the bench and interfaced to a datalogger (CR1000; Campbell Scientific). Measurements were recorded at 60-min intervals. Supplemental lighting was delivered by 1000-W high-pressure sodium lamps (P.L. Light Systems Inc., Beamsville, ON, Canada) used for 16 $h \cdot d^{-1}$ (0500–1900 HR) that provided a photosynthetic photon flux density of 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Seedlings were irrigated as needed using acidified tap water that had an EC of 0.8 $mS \cdot cm^{-1}$, pH of 7.3, and 195 $mg \cdot L^{-1}$ calcium carbonate ($CaCO_3$); furthermore, it contained (in $mg \cdot L^{-1}$) 0.2 nitrate nitrogen (NO3-N), 0.4 phosphorus (P), 3.0 potassium (K), 96.0 calcium (Ca), 38.0 magnesium (Mg), 51.0 sulfur (S), 0.4 iron (Fe), 0.0 manganese (Mn), 0.0 boron (B), 14 sodium (Na), and 36 chloride (Cl).

Transplanting occurred on 18 May 2023 and 14 Aug 2023 for tomato, and on 21 May 2023 and 17 Sep 2023 for pepper during the first and second experimental runs, respectively. Uniform seedlings were individually transplanted into 4-inch square containers (10.2-cm) filled to the same weight (260 ± 10 g) with horticulture-grade substrate (BM7 35% North Bark; Berger, QC, Canada) that was previously moistened to level four based on a visual subjective moisture scale (Fisher 2013). The substrate was composed of 50% coarse peatmoss, 35% pine bark, and 15% horticultural perlite and had an EC of 1.4 $mS \cdot cm^{-1}$ and pH of 6.0. The fertilizer starter charge provided an average of 71 $mg \cdot L^{-1}$ nitrate (NO_3-N) and 23 $mg \cdot L^{-1}$ ammonium (NH_4-N) (Nitroform© 39N–0P–0K; Allied Nutrients, Wichita, KS, USA).

Before starting the experiment, a substrate moisture sensor (5TE PRO-CHECK; Meter Group, Inc., Pullman, WA, USA) was calibrated for the substrate and fertilizer to be used in the experiment based on the procedures described by Nemali et al. (2007). For this purpose, the sensor was inserted completely into three substrate samples placed in 4-inch containers at 25%, 50%, 75%, or 100% container capacity with EC levels of 0.5, 1.0 or 1.5 $mS \cdot cm^{-1}$ that were under air temperatures of 21, 24, or 27 °C. An equation was generated based on these data points to calculate the target VWCs to be evaluated.

Production phase. After transplanting, plants of both species were divided in two fertilizer groups that were placed on two separate benches within the same greenhouse compartment used during propagation. Plants on one bench only received tap water and, thus, relied on the fertilizer starter charge in the substrate throughout the production phase. Plants on the other bench received a complete fertilizer solution (Peter's Professional 15N–2.2P–12.5K with micronutrients; ICL Specialty Fertilizer; Summerville, SC, USA) once per week at a concentration of 100 $mg \cdot L^{-1}$ N. Fertilizer groups were kept in separate benches to minimize potential cross-contamination when manually irrigating plants.

Within each bench, plants were randomly assigned to one of four VWC treatments: 0.15, 0.30, 0.45, or 0.60 $m^3 \cdot m^{-3}$. There were eight treatment replications arranged in a completely randomized design. Each replication had six containers of plants from one species placed within a netted tray (25 cm × 36 cm), which served as subsamples of an experimental unit. The substrate VWC from three random plants per experimental unit was measured daily between 0800 and 1100 HR using the moisture sensor previously described. After each measurement, the average VWC for each treatment was calculated, and plants were hand-irrigated to container capacity when the average value for all measured plants in a treatment reached or was below the target substrate VWC. The number of

Received for publication 22 Aug 2024. Accepted for publication 5 Nov 2024.

Published online 30 Dec 2024.

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Financial support was received from the United States Department of Agriculture (USDA) National Institute of Food and Agriculture, Multistate Research Project NE-2335: Resource Optimization in Controlled Environment Agriculture. We thank Pan American Seed Co. and Syngenta Flowers for donating seed.

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https://doi.org/10.21273/HORTTECH05529-24

irrigation events was recorded for each treatment.

Temperature and RH setpoints in the greenhouse were kept at 24/22 °C (day/night) and 65%, respectively. No carbon dioxide (CO_2) supplementation was provided, but CO_2 was maintained at ambient levels by active ventilation, as measured periodically with a portable CO_2 sensor (GM70D; Vaisala Corporation, Helsinki, Finland). The same sensors that were previously described were used to record environmental data throughout the experiment.

The production phase ended when most plants had a visible flower at anthesis, which occurred on 8 Jun 2023 and 4 Sep 2023 for tomato (22 d after transplanting), and on 3 Jul 2023 and 30 Oct 2023 for pepper (44 d after transplanting) during the first and second experimental runs, respectively. The average number of irrigation events for tomato and pepper plants treated with 0.15, 0.30, 0.45, or 0.60 $m^3 \cdot m^{-3}$ VWC were 6 and 8, 8 and 14, 11 and 17, or 15 and 19, respectively.

When the production phase ended, the leachate EC and pH of two plants per experimental unit were measured using a portable EC/pH meter (HI9813-6; Hanna Instruments, Carrollton, TX, USA) following the pour-through method (LeBude and Bilderback 2009). Then, four random plants per experimental unit were destructively harvested. Shoot height was measured from the substrate surface to the tallest growing point. The average canopy width was determined by measuring the widest diameter and width perpendicular from the widest diameter. The chlorophyll concentration was measured using a chlorophyll meter (MC-100; Apogee Instruments), and data were averaged based on multiple measurements. For tomato, three leaflets from the third largest leaf of each plant were measured. For pepper, three leaves (≥4 cm) that were three nodes below the apical meristem were measured. The number of flower clusters was counted and plant vigor was measured using a visual subjective scale as follows: 1 = compact plant, sparse canopy, too small for the container; 2 = intermediate branch spread and/or height, sparse canopy, suitable for the container; 3 = long branch spread and/or height, dense canopy, suitable for the container; and 4 = large plant, dense canopy, too large for the container. Plant quality was also measured using a visual subjective scale as follows: 1 = unsalable; 2 = below average quality; 3 = average quality; 4 = above average quality; and 5 = premium quality. After all these measurements were completed, shoots of two plants per experimental unit were severed at the substrate surface and were placed in a forced-air oven at 65 °C for 3 d. Then, shoots were weighed to determine the shoot dry weight (SDW).

Postproduction phase. The remaining four plants per experimental unit were irrigated to container capacity with the same fertilizer solution previously described, which marked the beginning of the postproduction phase. Two plants per experimental unit were randomly selected to measure the time to reach different wilting stages. For this purpose, plants were randomly placed in another bench in the same greenhouse compartment, and no additional irrigation was provided. All plants were visually assessed daily using a subjective scale as follows: 0 = no signs of wilt; 1 = slight wilting in less than half of all leaves; 2 = slight wilting in all leaves; 3 = severe wilting in all leaves with slight curling; 4 = major leaf curling in more than half of all leaves; 5 = plant death, after which plants were discarded.

The other two plants per experimental unit were kept in the same greenhouse compartment and irrigated as needed with tap water. After 1 week, the EC and pH of those plants were measured using a portable meter following the pour-through method. Then, plants were transplanted into 8-inch-diameter (20.3-cm) azalea plastic containers (3.1 L) (BWI; Nash, TX, USA) filled with the same substrate previously described and top-dressed with 12 g of controlled-release fertilizer (12N–1.7P–9.1K PLUS calcium nitrate; Florikan, Sarasota, FL, USA). Plants were randomly placed on two benches within the same greenhouse compartment on 15 Jun 2023 and 11 Sep 2023 for tomato, and on 10 Jul 2023 and 6 Nov 2023 for pepper during the first and second experimental runs, respectively. Plants were grown to harvest to assess differences in fruit yield and irrigated as needed with tap water when the substrate reached level three based on the visual subjective moisture scale previously described.

The first harvest for tomato occurred on 27 Jun 2023 and 16 Oct 2023 during the first and second experimental runs, respectively, when all plants had at least three fully mature fruit. Then, fruit of tomato plants were harvested weekly until the final destructive harvest, which occurred on 18 Jul 2023 and 30 Oct 2023 during the first and second experimental runs, respectively. Pepper plants were only harvested once before the final destructive harvest, when all plants had at least three fully mature fruit, which occurred on 15 Aug 2023 and 14 Jan 2024 during the first and second experimental runs, respectively. The number of mature fruit was recorded during each harvest and the number of immature fruit (≥1 cm) was recorded during the final harvest to calculate the total number of fruit from each plant. Before the final harvest, the leachate EC and pH, chlorophyll concentration, shoot height, canopy width, and SWD from all remaining plants were measured following the procedures previously described. During the first and second experimental runs, the average daily temperature, RH, and DLI (± standard deviation) were 27.3 ± 9.7 °C, 67 ± 12%, and 18.7 ± 3.7 $mol \cdot m^{-2} \cdot d^{-1}$, respectively, and 23.8 ± 3.7 °C, 43 ± 5%, and 12.6 ± 2.4 $mol \cdot m^{-2} \cdot d^{-1}$, respectively.

Data analyses. The experiment used a completely randomized design, and data were analyzed separately for each species. Because fertilizer groups were kept on separate benches and, thus, were not randomized within the experimental design, data were subject to separate analyses of variance. However, trends between the two fertilizer groups were compared to provide points of reference for each response variable. Data collected from each experimental unit (subsamples) were averaged and treated as a single data point per replication. Data were pooled between the two experimental runs because variances between experiments were not different and the statistical interactions between treatment and replication were not significant ($P >$ 0.05) (n = 16). A regression analysis was conducted to compare responses to the different VWC treatments. Both a linear fit and a quadratic fit of all variables were evaluated, and the best fit was selected based on the r^2 value for each model. Then, the significance of each model was analyzed and equations were only presented when significant ($P \leq 0.05$). All data were analyzed using statistical software (Posit, RStudio 2023; RStudio, Boston, MA, USA).

Results and discussion

Surprisingly, VWC had only minor effects on growth, quality, and fruit yield, regardless of species (Figs. 1–3). However, limiting fertilizer application during production had large effects on most measured variables. In general, plants irrigated with only tap water during the production phase were shorter, had less biomass, and produced less fruit than those that received fertilizer. Our findings are consistent with those of others who have evaluated different fertilizer concentrations during the production of vegetable and ornamental bedding plants (Aminifard et al. 2012; Bergstrand 2022; Cheng et al. 2021; Gao et al. 2023; Harp and Pulatie 2008; Park and Faust 2021, 2023; Zhang et al. 2022). However, the general lack of response to VWC differs from the findings of others who have shown that reducing VWC with CWD helps produce small containerized plants (Alem et al. 2015; Currey et al. 2019; van Iersel et al. 2010; Zhen et al. 2014). These differences are likely related to variations in the irrigation methods used to apply CWD, as in the aforementioned studies, VWC was maintained at the thresholds being evaluated as treatments and thus, substrates never reached container capacity. In contrast, plants in our study were thoroughly watered with every irrigation event, similar to commercial production practices (Mack et al. 2017). The sustained drought stress imposed on plants in previous studies (Alem et al. 2015; Currey et al. 2019; van Iersel et al. 2010; Zhen et al. 2014) most likely explains the larger effects of CWD for controlling height and overall growth compared with our findings. It appears that maintaining substrate VWC within thresholds that continuously impose drought stress is necessary when aiming to control plant growth with CWD. Accordingly, in a study that evaluated different irrigation management strategies for poinsettia (*Euphorbia pulcherrima*), Gent et al. (2016) showed that plants that were partially saturated with each irrigation event were shorter and had less fresh weight than those that were fully saturated.

The only growth variables that responded to VWC during the production phase were the shoot height of fertilized tomato plants and SDW of both fertilized and unfertilized tomato plants (Fig. 1A, E). Similar results were reported by Wang and Xing (2016), who found that tomato plants irrigated at 50% container capacity had a lower SDW than those irrigated to container capacity. In addition, in a study that evaluated the effect of CWD on height control of poinsettia, Alem et al. (2015) reported that plants grown with VWC of 0.20 $m^3 \cdot m^{-3}$ had 24% lower SDW than those grown with VWC of 0.40 $m^3 \cdot m^{-3}$. The authors also found that using CWD was more effective for maintaining shoot height within target levels compared with that maintained with the application of PGRs.

Pepper plants were generally unresponsive to VWC, but they were larger and more productive when treated with fertilizer compared with those irrigated with only tap water during the production phase (Figs. 1–3). Liu et al. (2012) reported that compared with tomato, the growth of pepper transplants was relatively unresponsive to different N concentrations in the fertilizer solution. Because peppers are often considered drought-tolerant during early plant development (Katerji et al. 1993), it is plausible that the general lack of response to VWC measured during our study is partly attributed to the duration of the production phase, which may not have been long enough to affect growth. Katerji et al. (1993) reported that once pepper plants start producing fruit, susceptibility to drought stress becomes more prominent, suggesting that changes in VWC in pepper may have been more significant with a longer production phase.

Although the chlorophyll concentration of tomato plants was unaffected by substrate VWC during the production phase, that of pepper plants that received fertilizer followed a negative quadratic response that was lowest under 0.60 $m^3 \cdot m^{-3}$, which was plausibly attributed to a slight saturation of the substrate that may have reduced nutrient uptake and, thus, affected chlorophyll synthesis (Fig. 4A, B). Similar results were reported by Jacobson et al. (2015) when evaluating different substrate moisture contents for the production of angelonia (*Angelonia angustifolia*).

Plants of both species irrigated with only tap water had relatively low chlorophyll concentrations at the end of the production phase ($\leq$22 $\mu mol \cdot m^{-2}$); this is typically associated with a low aesthetic quality because it tends to be related to the greenness of plants (Ferrante et al. 2012; Wang et al. 2005; Zhang et al. 2022) (Fig. 4A, B). However, the chlorophyll concentration of those same plants measured 1 week after the production phase ended increased by an average of 39% in tomato and 19% in pepper after a single fertilizer application (Fig. 4C, D). This quick increase suggested that when strategies such as fertilizer restriction for height control are used, applying fertilizer at least 1 week before shipping to retail may help increase the greenness of plants; however, the long-term effect of this recommendation is unknown. In a study that evaluated various fertilization strategies to improve the postproduction performance of petunia (*Petunia* ×*hybrida*), Park and Faust (2021) found that although plants can benefit from 300 to 600 $mg \cdot L^{-1}$ N applied through pulse fertilization at the end of the production phase, the chlorophyll concentration was unaffected by pulse fertilization after only 1 week. Ebba et al. (2021) also found that although applying a large concentration of N (400 $mg \cdot L^{-1}$) immediately after the production phase ended improved the quality of petunia plants, the chlorophyll concentration started to decrease soon after the postproduction phase started. The authors suggested that when selecting residual fertilizer strategies, providing a continual and adequate supply of nutrients is important for vigorous crop species. In our study, the chlorophyll concentration was unaffected by VWC at the end of the postproduction phase, and differences between plants in the two fertilizer groups became smaller, which was expected, and plants had uniformly received controlled-release fertilizer several weeks prior (Fig. 4E, F).

Plants of both species that received fertilizer reached wilting stages of 1, 3, and 5 sooner than those that were irrigated with only tap water during the production phase (Fig. 5A–F).

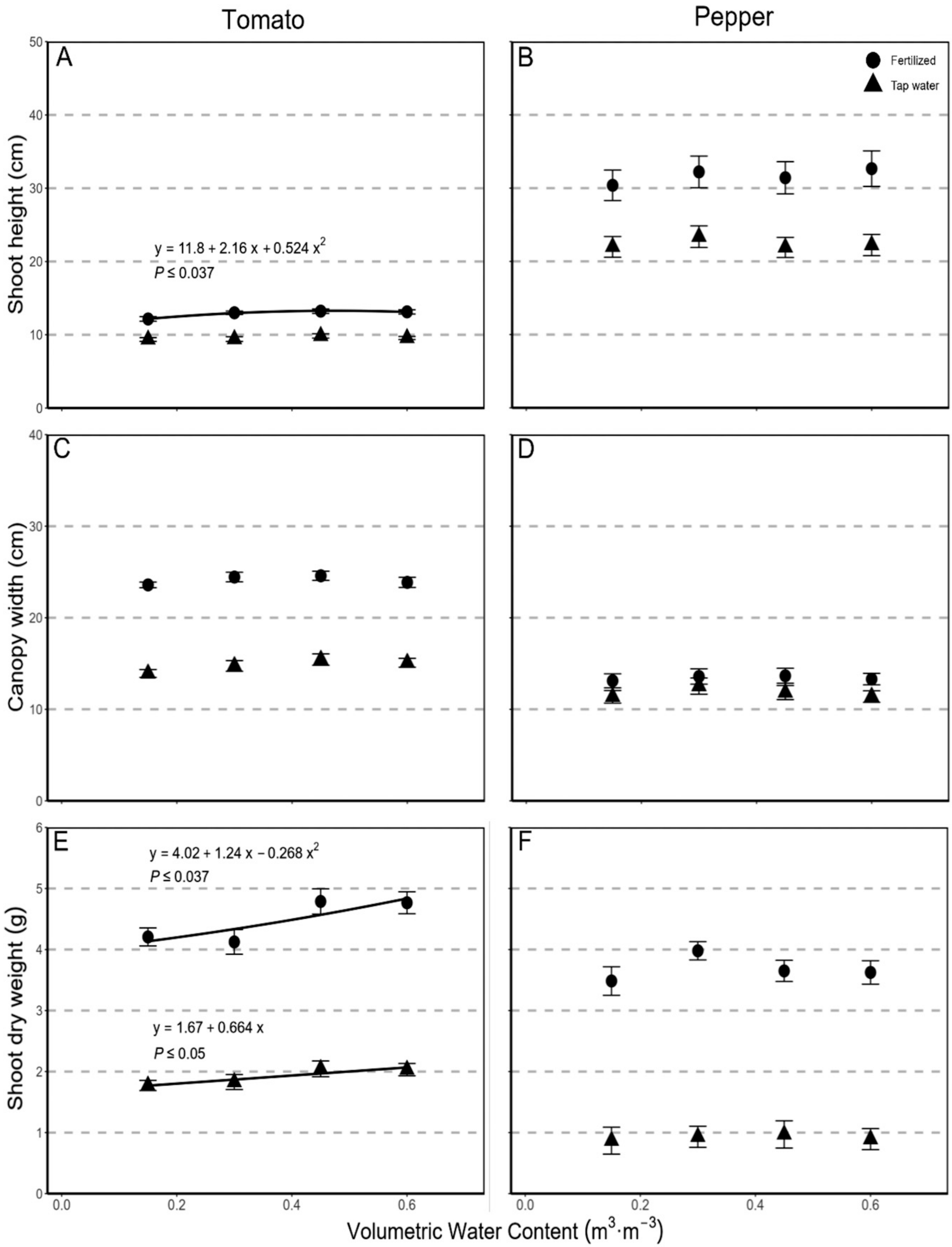

Fig. 1. Effects of the volumetric water content and fertilizer use on shoot height (A and B), canopy width (C and D), and shoot dry weight (E and F) of compact tomato and pepper plants grown in a greenhouse for 22 d and 44 d, respectively. Each data point represents the mean of eight replications during two experimental runs ± standard error (n = 16). Equations and *P* values are only presented when the linear or quadratic response to increasing the volumetric water content was statistically significant ($P \leq 0.05$).

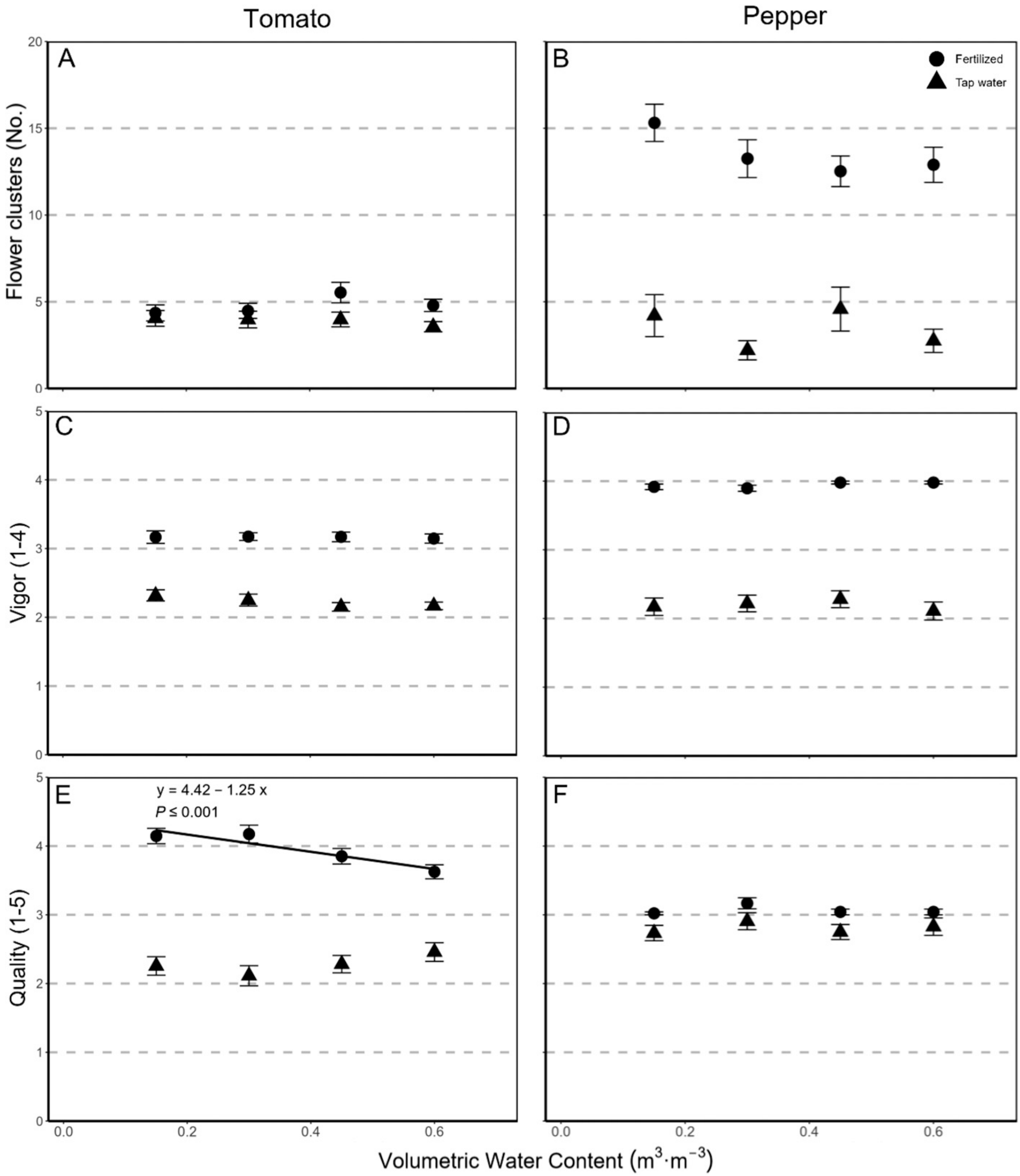

Fig. 2. Effects of volumetric water content and fertilizer use on flower number (A and B), vigor (C and D), and plant quality (E and F) of compact tomato and pepper plants grown in a greenhouse for 22 d and 44 d, respectively. Each data point represents the mean of eight replications during two experimental runs ± standard error (n = 16). Equations and P values are only presented when the linear or quadratic response to increasing the volumetric water content was statistically significant ($P \leq 0.05$).

However, the response to VWC was only significant in fertilized tomato plants, which followed a negative quadratic trend for the time to reach wilting stage 1 but a linear positive trend for the time to reach wilting stage 3. Jacobson et al. (2015) showed that smaller angelonia plants grown under low substrate VWC never showed signs of wilt in a simulated retail environment. However, our results suggest that withholding fertilizer has a larger

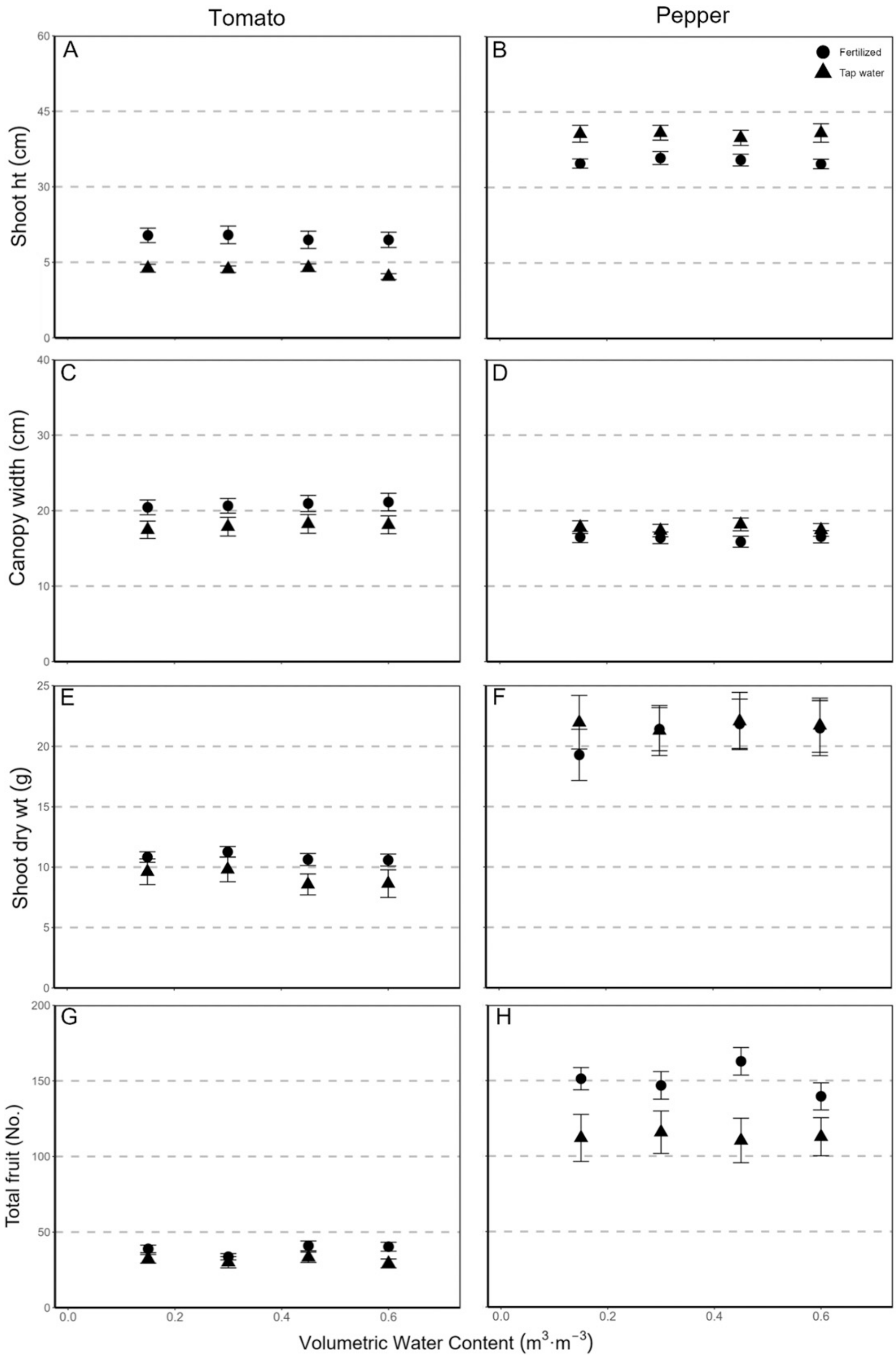

Fig. 3. Postproduction effects on shoot height (A and B), canopy width (C and D), shoot dry weight (E and F), and fruit yield (G and H) of compact tomato and pepper plants grown in a greenhouse using different volumetric water content and fertilizer treatments. Each data point represents the mean of eight replications during two experimental runs ± standard error (n = 16). For all variables, the response to increasing the volumetric water content was not statistically significant ($P > 0.05$).

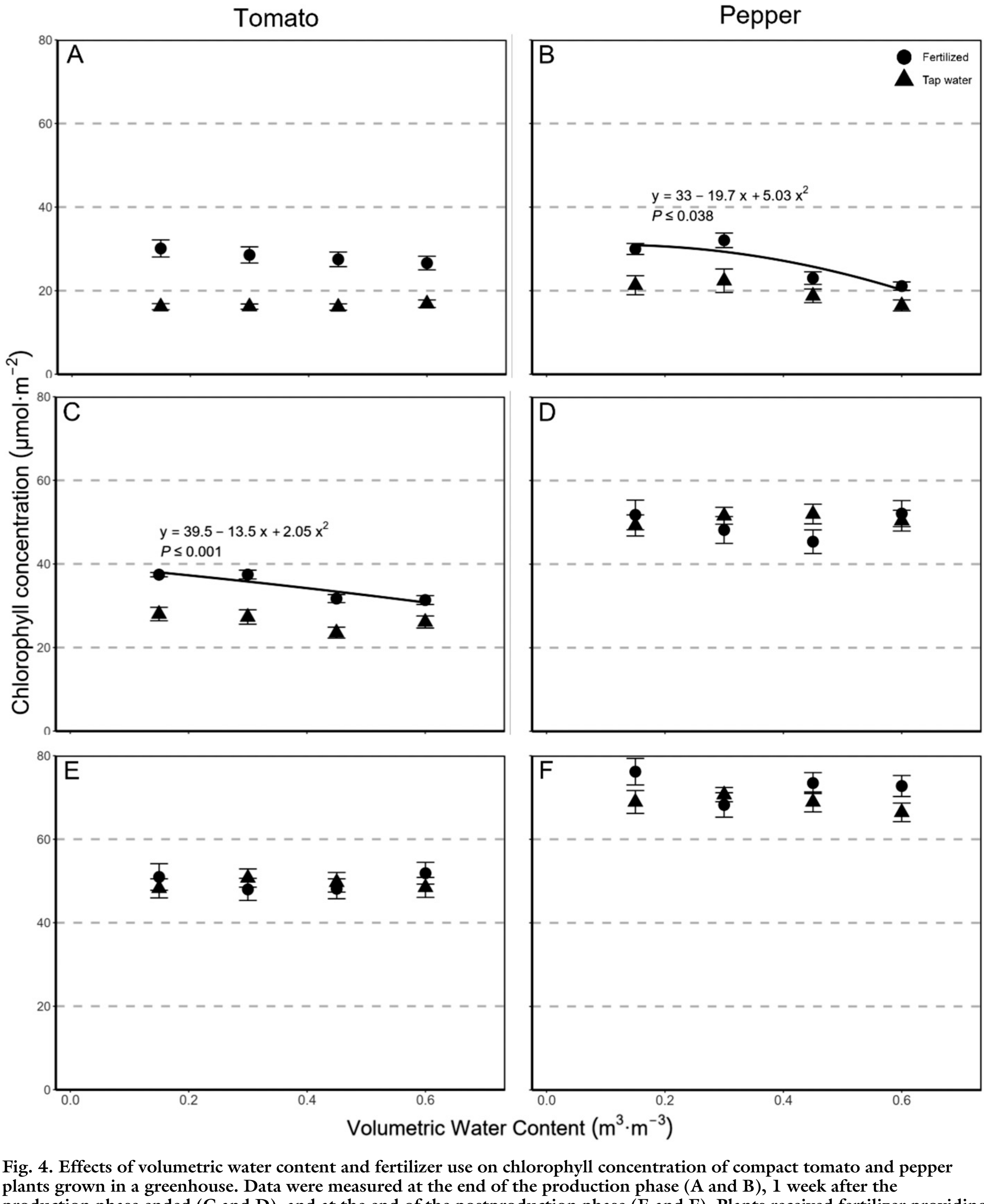

Fig. 4. Effects of volumetric water content and fertilizer use on chlorophyll concentration of compact tomato and pepper plants grown in a greenhouse. Data were measured at the end of the production phase (A and B), 1 week after the production phase ended (C and D), and at the end of the postproduction phase (E and F). Plants received fertilizer providing 100 mg·L^{-1} N at the end of the production phase and were top-dressed with controlled-release fertilizer after transplanting into larger containers 1 week after starting the postproduction phase. Each data point represents the mean of eight replications during two experimental runs ± standard error (n = 16). Equations and *P* values are only presented when the response to increasing the volumetric water content was statistically significant ($P > 0.05$).

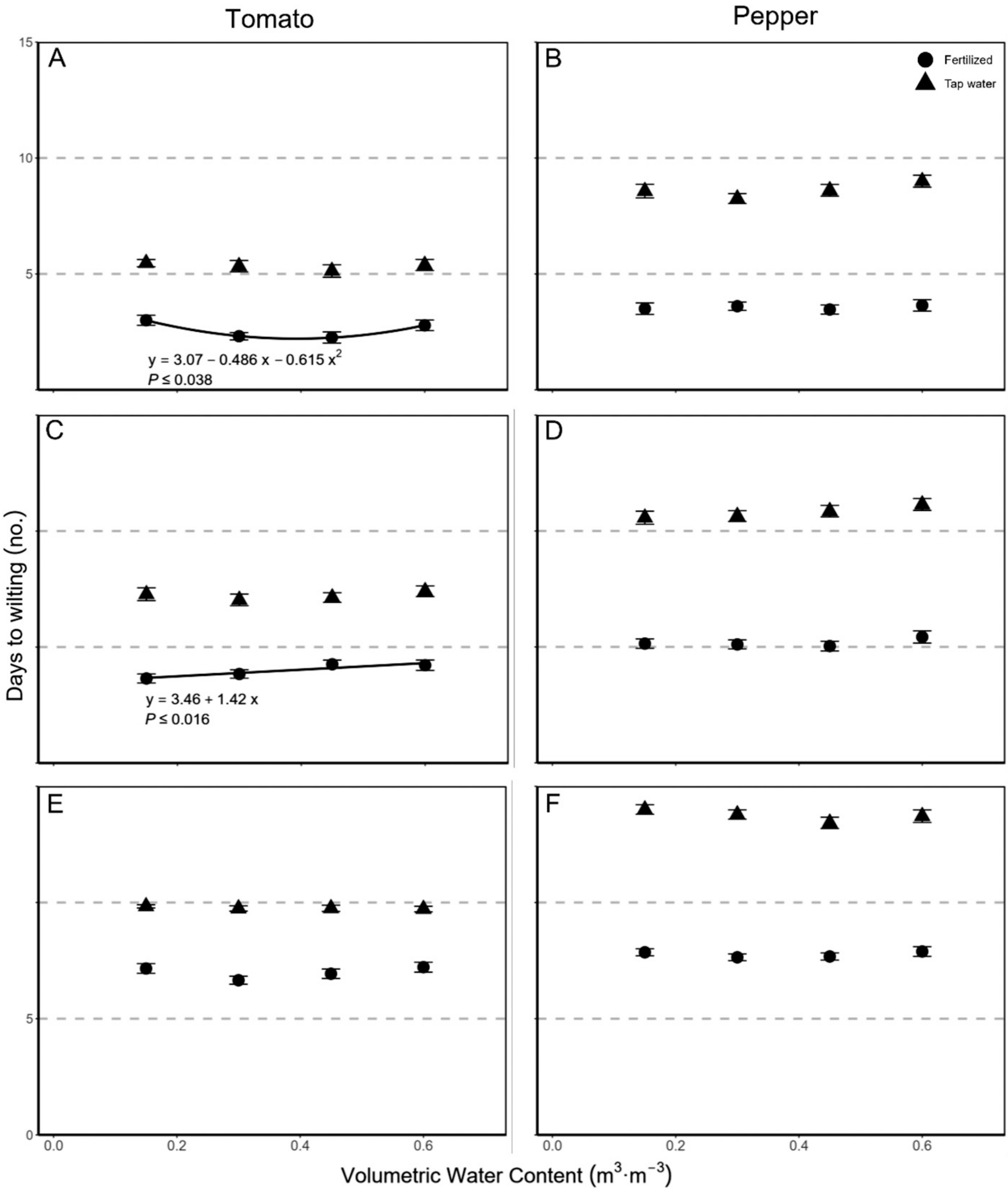

Fig. 5. Effects of volumetric water content and fertilizer use on the time for compact tomato and pepper plants to reach wilting stages 1 (A and B), 3 (C and D), and 5 (E and F), where 1 = slight wilting in less than half of all leaves; 3 = severe wilting in all leaves with slight curling; and 5 = plant death. Each data point represents the mean of eight replications during two experimental runs ± standard error (n = 16). Equations and *P* values are only presented when the linear or quadratic response to increasing the volumetric water content was statistically significant ($P \leq 0.05$).

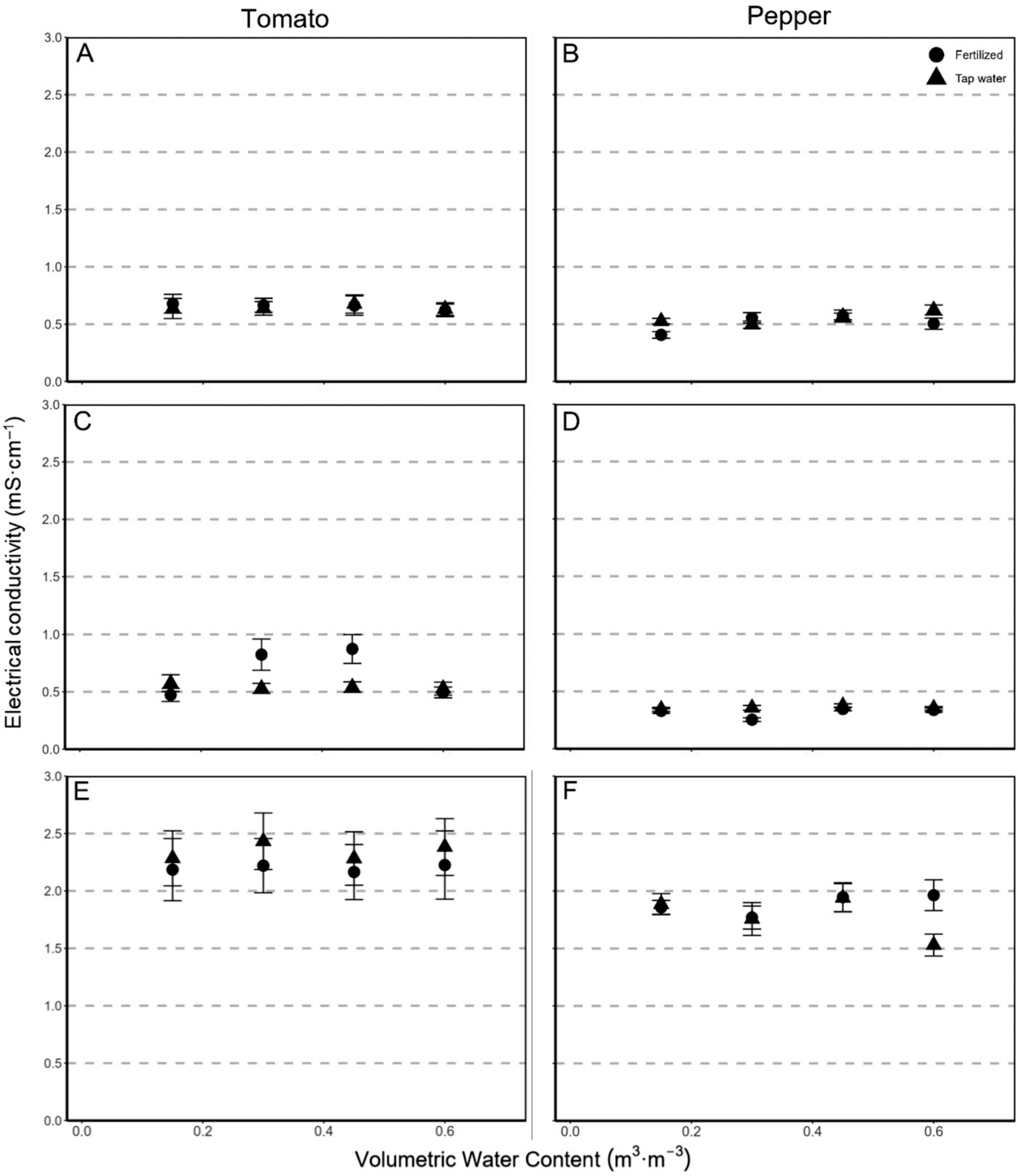

Fig. 6. Measurements of leachate electrical conductivity of compact tomato and pepper plants grown in a greenhouse using different volumetric water content and fertilizer treatments. Data were measured at the end of the production phase (A and B), 1 week after the production phase ended (C and D), and at the end of the postproduction phase (E and F). Plants received fertilizer providing 100 mg·L^{-1} N at the end of the production phase and were top-dressed with controlled-release fertilizer after transplanting into larger containers 1 week after starting the postproduction phase. Each data point represents the mean of eight replications during two experimental runs ± standard error (n = 16). For all variables, the response to increasing the volumetric water content was not statistically significant ($P > 0.05$).

effect on delaying wilt progression than reducing substrate VWC. These results are likely attributable to differences in the transpiration rate as a factor of plant size because it is widely known that that as plant growth increases, whole plant transpiration increases (Parkhurst and Loucks 1972). Plants irrigated with only tap water during the production phase were generally smaller and likely transpired less than those that received fertilizer, partially explaining why they reached the different wilting stages at a later time. These findings showed that another potential advantage of producing smaller, shorter plants is delaying wilt progression, which could prolong the esthetic appeal of bedding plants in retail environments.

Both the leachate EC and pH were unaffected by substrate VWC (Fig. 6A–F), and values were relatively similar between plants in the two fertilizer groups across different measurement times. These results were surprising because there were various growth and quality differences between plants that were fertilized and those irrigated with only tap water (Figs. 1–5). In general, EC values at the end of the production phase and those measured 1 week later, after plants had been fertilized, were below the recommended range of production for vegetable bedding plants (1.0 to 1.5 $mS\cdot cm^{-1}$) (Leth 2022). In contrast, average pH values across fertilizer groups were 7.0 and 6.8 pH for tomato and pepper plants, respectively (data not shown), which were higher than the recommended range of 5.3 to 5.8 (Leth 2022). One plausible explanation for the lack of differences in leachate EC may be attributed to the different plant sizes that resulted from the two fertilizer treatments. Plants that were fertilized were generally larger and, thus, likely used most of the nutrients applied, which explains why they did not show visual signs of chlorosis. In contrast, plants grown with only tap water were smaller and visually chlorotic at the end of the production phase, which can be explained by the lack of fertilizer used in their production. This is further supported by our chlorophyll concentration results, which showed that plants that were fertilized had higher chlorophyll levels than those of plants irrigated with only tap water (Fig. 4A, B).

Conclusion

Based on our overall findings, limiting fertilizer application during production can have a larger effect on plant growth and yield than restricting VWC when the substrate is brought back to container capacity after each irrigation event. For example, plants of both species irrigated with only tap water during the production phase were shorter, had less biomass, and produced less fruit than those that received fertilizer. In contrast, shoot height and SDW of tomato were the only two growth variables affected by VWC, and pepper plants were generally unresponsive to differences in VWC. Although plants irrigated with only tap water during production had a lower chlorophyll concentration than that of plants that were fertilized, they quickly greened after receiving a single dose of fertilizer solution. This finding suggests that using a residual fertilizer strategy before shipping may help increase plant greenness when height-control treatments that induce chlorosis are used. Furthermore, wilt progression was slower in plants of both species irrigated with only tap water during the production phase, likely because of their smaller size that limited water demand. During the postproduction phase, the only differences in growth and yield were measured for pepper plants, and fertilized plants were larger and produced more fruit compared to those irrigated with only tap water during the production phase. Based on our results, growers should limit their fertilizer use when trying to produce compact vegetable plants and possibly rely on only the fertilizer starter charge incorporated into the substrate during short production cycles. However, reducing the irrigation frequency may not have an effect on height and overall growth if plants are watered thoroughly each time.

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