Growth Rate and Nutrient Uptake of Basil in Small-scale Hydroponics

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Additional index words. greenhouse production, herbs, indoor gardening, *Ocimum basilicum*, pick-and-eat

Abstract. **To identify practices that may simplify the use of small-scale hydroponic systems for indoor gardening, we compared two nutrient solution management treatments for basil (*Ocimum basilicum*) production. Experiments were conducted for 8 weeks to evaluate the effect of biweekly replacement of the nutrient solution (W) vs. biweekly fertilizer addition without nutrient solution replacement (W/O) on growth and nutrient uptake of basil 'Genovese Compact' grown in either a greenhouse or an indoor environment. Greenhouse day/night temperature was 29/24 ± 4 °C, relative humidity (RH) was 65 ± 4%, and daily light integral (DLI) was 26.1 mol·m^{-2}·d^{-1}. The indoor environment had a constant ambient temperature of 21 °C, RH of 65%, and DLI of 9 mol·m^{-2}·d^{-1} provided by broadband white lamps. Four plants were grown in 7.6-L replicate hydroponic systems, with 178 mg·L^{-1} N from a complete nutrient solution in two experimental runs. Shoot fresh and dry mass, leaf number, and leaf area showed an increasing quadratic trend over time when plants were grown in the greenhouse. In contrast, growth over time was linear for plants grown indoors. Within each environment, solution management treatment did not affect growth, indicating that the simpler W/O strategy was adequate under these conditions. Plants grown in the greenhouse required more frequent refill water applications compared with indoors, which resulted in three to four times more refill water applied. Because indoor-grown plants had a decreased growth rate, nutrient uptake rate, and volume of water applied compared with plants grown in the greenhouse, electrical conductivity (EC) for the W/O treatment increased over time. Final nutrient solution concentration was highest for indoor-grown plants under the W/O treatment, and final tissue nutrient concentration was higher for plants grown indoors compared with the greenhouse. Final nutrient uptake (dry mass × nutrient concentration) was higher for plants grown in the greenhouse rather than indoors. Considering that EC increased in the solution of indoor-grown plants under W/O, an appropriate strategy using this treatment would require reducing fertilizer input indoors. To refine simple and robust fertilizer management strategies for indoor gardeners, further research is needed to test variables such as different plant species, cultivars, and water qualities.**

According to a national gardening survey published in 2018, over 77% of U.S. households are involved in gardening activities, and 30% of those activities take place indoors (NGA, 2018). Indoor food gardening, which integrates the production of edible plants (e.g., herbs, greens, and low-profile fruiting vegetables) with indoor farming, provides an opportunity to support the gardening experience for consumers with limited access to a growing space (from now on referred to as "indoor gardeners") (Halleck, 2018). However, compared with large-scale commercial production, indoor food gardening has received limited research attention. Most research-based information about growing plants indoors aims to maximize yield by providing optimal cultural practices and environmental conditions. In contrast, indoor gardeners tend to grow plants in a variety of environmental settings such as residential living rooms and kitchens, classrooms, or office spaces, which are conditioned for human comfort and function, and may not be conducive to optimal plant growth and development. Information is lacking about plant responses to practices and environments that differ from those recommended for commercial production, especially regarding the minimum inputs required to effectively provide a continuous supply of fresh produce for indoor gardening.

Hydroponic systems are popular among hobbyist gardeners because they offer the opportunity to reduce or eliminate weeding and watering, which are considered two of the most burdensome tasks with conventional outdoor gardening (Resh, 2015). In addition, water and fertilizer conservation is a feature of most hydroponic systems (Sharma et al., 2018), making them attractive alternatives for gardening. Hydroponics systems can be "open," where excess or runoff nutrient solution is not reused; or "closed," where nutrient solution is collected and reused. Indoor gardeners tend to prefer closed systems because these offer flexibility in terms of system design and nutrient solution handling and disposal (Resh, 2015). However, closed hydroponic systems require constant monitoring of pH and salt levels, which can become challenging for indoor gardeners.

Maintaining a balanced nutrient solution within hydroponic systems requires periodic water refills, fertilizer replenishment, and/or complete nutrient solution replacements (Christie, 2014; Resh, 2015). Several strategies can be implemented to manage the nutrient solution in closed hydroponic systems. One common strategy consists of replacing the entire solution after 1 (Jones, 2005; Lykas et al., 2006) or 2 weeks of use (David et al., 1996; Samarakoon et al., 2006; Spensley et al., 1978). Another strategy recommends the constant monitoring of ions, considering the different uptake rate of nutrients by plants (e.g., active, intermediate, and passive) (Bailey et al., 1988). However, factors such as system design and capacity, environmental conditions, water quality, type and quantity of fertilizer, number and target size of plants and their species, among others, can affect nutrient uptake and thus should be considered when handling the solution, particularly if it is being recirculated and recycled during the production cycle of a crop (Brooke, 2003; Bugbee, 2004).

Commercial growers tend to constantly monitor the electrical conductivity (EC) as an indication of nutrient concentrations in a solution (Jones, 2005; Mackowiak et al., 1989). However, EC largely reflects the accumulation of passive ions over time and thus can be a misleading indicator of nutrient availability, as it does not represent the quantity of nutrient ions absorbed by plants, nor does it differentiate among those being taken up by plants (Bugbee, 2004). There is a lack of consensus about the most appropriate method to manage nutrient solutions within closed hydroponic systems. Discarding the nutrient solution at regular intervals can be considered burdensome, time consuming, and wasteful when undertaken too frequently (Bugbee, 2004; Jones, 2014). In addition, the difference in environmental conditions (e.g., light, temperature, humidity, airflow, among others) between commercial hydroponic production (which typically occurs in a greenhouse) and indoor gardening is also expected to affect plant growth and development. Therefore, solution management strategies should differ when plants are grown in a

Received for publication 15 Nov. 2019. Accepted for publication 21 Jan. 2020.
Published online 28 February 2020.
Financial support was received from the USDA National Institute of Food and Agriculture, Multistate Research Project NE1835: Resource Optimization in Controlled Environment Agriculture. We thank the USDA-ARS Floriculture and Nursery Research Initiative #58-3607-8-725, the Scotts Co., and industry partners of the Floriculture Research Alliance at the University of Florida (floriculturealliance.org) for supporting this research.
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greenhouse following commercial practices, or in an indoor environment used for indoor gardening.

Basil (*Ocimum basilicum*) plants are suitable for indoor gardening as they can successfully be grown in a variety of conditions such as temperature ranges from 10 to 27 °C, EC from 0.5 to 4.0 dS·m^{-1}, pH from 4.3 to 8.2, and daily light integrals (DLIs) as low as 4 mol·m^{-2}·d^{-1} (Moya et al., 2014; RSADA, 2012; Solis-Toapanta and Gómez, 2019; Walters and Currey, 2018; Wortman, 2015). This versatility may enable basil to outperform other edible crops that can be used for indoor gardening. For example, basil can be produced for an extended period, whereas salad greens and microgreens must be harvested and planted several times per year to supply a continuous harvest. Similarly, compared with some fruiting crops, basil does not need pollination, requires minimal training when pinched regularly, and can tolerate a wide range of EC values in the nutrient solution (Walters and Currey, 2018). In addition, indoor gardeners could start harvesting leaves as early as 6 weeks after sowing, which, if performed in moderation, should not affect further plant growth and development (RSADA, 2012). Finally, basil could be less susceptible to unintentional neglect (e.g., due to time and effort constraints by indoor gardeners) compared with other crops and thus is a good candidate for successful indoor gardening experiences.

The specific objectives of this study were to: 1) compare final growth and nutrient uptake of hydroponic basil plants grown with or without a nutrient solution replacement in a greenhouse or an indoor environment; and 2) characterize growth over time in both environments using a nutrient solution replacement every 2 weeks. We hypothesized that in both environments, plant growth would be higher with a biweekly nutrient solution replacement because nutrient concentrations would be close to ideal levels. In contrast, nutrients and other ions would accumulate or become depleted in the reservoir without a nutrient solution replacement. We further hypothesized that plants grown in a greenhouse would produce more biomass and have higher nutrient uptake compared with those grown in an indoor environment because of faster growth rates induced by close-to-optimal environmental conditions.

Materials and Methods

Plant material and growing conditions. Seeds of basil 'Genovese Compact' (Johnny's Selected Seeds, Winslow, ME) were sown into 50-cell trays (34 mL individual cell volume) of stabilized peatmoss plugs (Black Magic, Hawthorne Hydroponics, Las Vegas, NV) on 16 Jan. 2018 and 16 Jan. 2019 for the greenhouse environment and on 2 Aug. 2018 and 20 Feb. 2019 for the indoor environment. Seeds were germinated in a growth room at a constant temperature of 23 °C and 80% relative humidity (RH), where broadband white light-emitting diode (LED) lamps (RAY66 PhysioSpec Indoor; Fluence Bioengineering, Austin, TX) provided a photosynthetic photon flux (*PPF*) of 100 µmol·m^{-2}·s^{-1} for 16 h·d^{-1}, resulting in a DLI of 5.8 mol·m^{-2}·d^{-1}. Until germination occurred, seedlings were irrigated as needed with tap water. After germination and before solution management treatments were applied, plants were fertilized every 2 d with a dilute nutrient solution of 4N–0P–0.8K plus 2N–1.3P–5.8K (Root Farm Nutrients; Hawthorne Hydroponics, Las Vegas, NV). The fertilizer concentration (in mg·L^{-1}) was 115.2 N (combining 19.2 NH_4-N and 96 NO_3-N), 22.5 P, 126.6 K, 76 Ca, 28.2 Mg, 32.2 S, 1.02 Fe, 0.3 Mn, 0.2 Zn, 0.08 Cu, 0.19 B, 0.01 Mo, 3.8 Na, and 33.7 Cl. Fertilizer was added to tap water with an EC of 0.44 dS·m^{-1}, pH 6.8, and 31.2 mg·L^{-1} $CaCO_3$ alkalinity, and containing (in mg·L^{-1}) 0.3N (combining 0.2 NH_4-N and 0.1 NO_3-N), 0.1 P, 1.7 K, 36.8 Ca, 23.4 Mg, 41.6 S, 0.01 Fe, 0.0 Mn, 0.0 Zn, 0.0 Cu, 0.03 B, 0.0 Mo, 11.5 Na, and 27.3 Cl.

At 22 d after sowing, uniform seedlings were selected and each experimental run was initiated. Four seedlings were transplanted into each replicate hydroponic system (23-cm width × 23-cm length × 19-cm height) using 5-cm-diameter net cups. Each 7.6-L hydroponic system was opaque and had a white plastic lid with four openings (20 cm apart) that held one net cup each. A clear plastic tube attached to an air pump (320 GPH Dual Diaphragm Air Pump, General Hydroponics, Santa Rosa, CA) provided continuous aeration. Bamboo stakes (40 cm tall) were used to provide physical support for the plants, which were secured as needed with twist ties.

Experimental design and solution management treatments. Two experiments were conducted in either a computer-controlled greenhouse in Gainesville FL ("greenhouse environment") or in a walk-in growth room ("indoor environment"), with two experimental runs per environment in 2018 and 2019. There were two treatments representing different nutrient solution management strategies in each environment. In the first treatment, the nutrient solution was completely replaced every 2 weeks ("W"), and nutrients were allowed to deplete over time between biweekly nutrient replacement events. In the second treatment, the nutrient solution was not replaced, but the same mass of fertilizer as in the W treatment was added every 2 weeks ("W/O"). Each experimental unit ("replicate hydroponic system") was an aerated deep-water culture hydroponic system with four basil plants. Water level was monitored daily and was refilled with tap water ("refill water") back to 7.6 L whenever the solution dropped to half of the solution (3.9 L), to maintain adequate water levels.

Fertilization. The commercial water-soluble fertilizer added every 2 weeks had a 10N–3.4P–13.3K formulation (The Scotts Co., Marysville, OH). The fertilizer concentration (in mg·L^{-1}) was 178 N (combining 16.9 NH_4-N and 160.8 NO_3-N), 62.7 P, 301.8 K, 92.2 Ca, 49.2 Mg, 53.2 S, 2.5 Fe, 0.5 Mn, 0.3 Zn, 0.2 Cu, 0.4 B, 0.06 Mo, 5.3 Na, and 2.7 Cl plus the additional ions in tap water. The pH was adjusted with an acid or a base (pH Down or pH Up, General Hydroponics) to 5.5–6.5 immediately after adding fertilizer, which added either phosphoric acid and citric acid, or potassium carbonate and potassium silicate, respectively.

Greenhouse environment. Plants were grown for 8 weeks inside a 75-m^2 polycarbonate greenhouse compartment in Gainesville, FL (lat. 29.6° N, long. 82.3° W). Air temperature, RH, and DLI were monitored with temperature and RH probes (HMP60-L; Campbell Scientific, Logan, UT), and quantum sensors (SQ512; Apogee Instruments Inc., Logan, UT) interfaced to a datalogger (CR1000; Campbell Scientific) and multiplexer (AM16/32B; Campbell Scientific), respectively. Replicate hydroponic systems were placed on top of two 4.6-m × 1.8-m metallic benches, with one temperature/RH probe and one quantum sensor per bench at midcanopy height, and measurements were made every 30 s and recorded at 60-min intervals. For experimental run 1 in 2018, the mean ±SD climate readings were day temperature 30 ± 4 °C, night temperature 24 ± 1.5 °C, RH 68 ± 4%, and DLI 28.4 mol·m^{-2}·d^{-1}. For experimental run 2 in 2019, the mean ±SD climate readings were day temperature 28 ± 5 °C, night temperature 23 ± 1 °C, RH 62 ± 5%, and DLI 23.7 mol·m^{-2}·d^{-1}.

Indoor environment. Following the same procedures as previously described, on 22 Aug. 2018 and 12 Mar. 2019, four basil plants were transplanted into each replicate hydroponic system and grown for 8 weeks inside a walk-in growth room set at a constant temperature of 21 °C. Plants were grown under a DLI of 9 mol·m^{-2}·d^{-1} (173 ± 5 µmol·m^{-2}·s^{-1}; 14-h·d^{-1} photoperiod from 0600 to 2000 HR) provided by broadband white LEDs. A light map was generated to determine the average *PPF* at midcanopy height using a spectroradiometer (SS-110; Apogee Instruments Inc.). The light output to achieve the target *PPF* was controlled with a dimmer (Solunar; Fluence Bioengineering). All hydroponic systems within each compartment were randomly rotated daily to minimize location effects within the experimental area. Average ambient air temperature inside the walk-in growth room was monitored with shielded temperature sensors (Elitech dataloggers; Elitech, Milpitas, CA).

Data collected. For the first experimental run in the greenhouse environment, two replicate hydroponic systems for the W treatment were destructively harvested every 2 weeks up until week 6, with four replicates of both the W and W/O treatments in the final harvest at week 8. For the second experimental run, four replicate hydroponic systems for the W treatment were destructively harvested every 2 weeks up until week 6, with four replicates of both the W and W/O treatments in the final harvest at week 8. In total, there were 22 and eight harvests of the W and W/O treatments, respectively, in the greenhouse. For the first and second experimental run in

the indoor environment, four replicate hydroponic systems for the W treatment were destructively harvested up until week 6, with four replicates of both the W and W/O treatments in the final harvest at week 8. In total, there were 40 and eight harvests of the W and W/O treatments, respectively, indoors.

At harvest, shoots were cut at the base of the stem near the substrate plug. The number of leaves (>1 cm) per plant was counted and total leaf area was measured using a leaf area meter (LI-3100C; LI-COR Biosciences, Lincoln, NE). Shoots (stem and leaves) were weighed with an electronic balance to obtain shoot fresh mass (SFM) and were oven-dried separately at 70 °C for 72 h to determine shoot dry mass (SDM). During the trial, basil plants were pinched 4 and 6 weeks after treatment initiation to prevent top-heavy greenhouse-grown plants from destabilizing the hydroponic reservoirs, or to maintain a consistent 20-cm height for indoor-grown plants. Pinched shoots were weighed per replicate hydroponic system, and mean values were added to the final SFM and SDM. Proportional parts of the cumulative dry tissue (including stems and leaves) were ground to obtain samples of at least 2 g used to monitor nutrient uptake. Tissue and nutrient solution samples were analyzed for each destructively sampled replicate hydroponic system to measure tissue nutrient concentration. Total Kjeldahl nitrogen (N) was measured by semiautomated colorimetry following procedures described by O'Dell (1993). Phosphorous (P), potassium (K), calcium, magnesium, sulfur, iron, manganese, boron, copper, zinc, and sodium concentrations were measured by inductively coupled plasma atomic emission spectrophotometry (Quality Analytical Laboratories, Panama City, FL). In addition, solution EC and pH were monitored with an EC and pH meter (HI 9813-6N waterproof; Hanna Instruments, Carrollton, TX) and recorded every week. The refill volume of water required to maintain reservoir levels above 3.9 L was recorded as a total volume for each replicate hydroponic system every 2 weeks.

Data analyses. Because environmental conditions (i.e., light, temperature, humidity, airflow, among others) in the greenhouse and indoors were different, data were subject to separate analyses of variance. However, statements comparing trends between each environment are included in the results and discussion sections to provide points of reference for each response variable. The experiments were replicated twice over time (2018 and 2019) and had a completely randomized design. Data were pooled between replications over time, as variances between experiments were not different and the statistical interactions between treatment and replication were not significant ($P \geq 0.05$). A regression analysis was conducted to compare growth trends measured for plants grown under both environments (greenhouse or indoors) for 8 weeks using SigmaPlot 13.0 (Systat Software, Inc., San Jose, CA). We evaluated a linear and quadratic fit for all growth variables. Based on the *r*-square value for each model, a linear fit was chosen for plants grown indoors and a quadratic fit for plants in the greenhouse. Final destructive harvest, EC, total refill water, and nutrient uptake data from both environments were subject to a student *t* test using the fit model procedure of JMP (version 12, SAS Institute Inc., Cary, NC).

Results

Within each environment, solution management treatment did not affect leaf area, leaf number, SFM, or SDM (Table 1). However, plants grown indoors had less growth than in the greenhouse. Growth over time was linear for plants grown indoors (Fig. 1), whereas all growth variables showed an increasing quadratic trend when plants were grown in the greenhouse. In addition, plants grown indoors required less frequent refill water applications, which resulted in approximately ¼ of the refill water volume compared with those grown in the greenhouse (Table 2). Although the refill water volume statistically differed between both solution management treatments within each environment, the volumes only differed by 10% in the greenhouse and 17% indoors. In both environments, final solution EC was higher for the W/O treatment than for the W treatment.

Figure 2A and B show the pattern of EC changes over time, which resulted from the combination of before and after biweekly fertilizer additions (W/O) or solution replacements (W), refill volumes (shown in Fig. 2C and D), and increasing plant growth and leaf area (shown in Fig. 1). The EC over time was higher for the W/O treatment than for the W treatment in both environments (Fig. 2), especially when plants were grown indoors. The highest solution EC was measured for the W/O treatment at week 6 indoors (5.5 $dS \cdot m^{-1}$). Refill water volume applied increased over time and was higher in the greenhouse than indoors for both solution management treatments. For example, plants grown indoors under the W/O treatment had 1.4, 9.5, 11.2, and 8.6 L less refill water applied than those grown in the greenhouse at weeks 2, 4, 6, and 8, respectively (Fig. 2C and D).

Table 3 shows the final nutrient solution concentration at week 8 that resulted in the W/O treatment from 8 weeks of nutrient depletion, addition of nutrients from tap water, and uptake by plants, whereas the W treatment shows the concentration changes from week 6 to 8. Regardless of nutrient solution management treatment, N, P, and K were almost completely depleted when plants were grown in the greenhouse. Furthermore, final nutrient solution concentration in the greenhouse was significantly higher for plants receiving the W/O treatment compared with the W treatment (Table 3), except for P and manganese, which did not differ. For plants grown indoors, final nutrient concentration was generally higher in the W/O compared with the W treatment. The N, P, and K concentrations in the solution were also higher for plants grown indoors than for those grown in the greenhouse. Micronutrient concentrations differed less than macronutrients between environments. For example, we measured 1.6 $mg \cdot L^{-1}$ of iron in the W treatment indoors compared with 1.5 $mg \cdot L^{-1}$ in the W treatment in the greenhouse.

There was little effect of nutrient solution management treatment within an environment on final tissue nutrient concentration, although plants grown indoors had higher values compared with those grown in the greenhouse (Table 4). The W/O treatment resulted in higher tissue concentration for N and P in the greenhouse and for iron indoors, compared with the W treatment. In general, and regardless of environment and solution management treatment, tissue nutrient concentrations were within published survey ranges (Bryson et al., 2014). The only exceptions were for N, magnesium, and iron, for which plants in the greenhouse had values below the survey ranges, and high K concentration for plants grown in the greenhouse and indoors.

Final N and P uptake (dry mass × nutrient concentration) was higher in plants grown in the greenhouse under the W/O treatment compared with the W treatment, and N uptake showed the same trend indoors (Fig. 3). Nutrient uptake was lower for plants grown indoors than in the greenhouse, which would primarily

Table 1. Final growth measured for basil plants grown inside a greenhouse or indoor environment for 8 weeks under one of two nutrient solution management treatments.

	Greenhouse		Indoors	
Growth parameters	W[z]	W/O	W	W/O
Leaf area (cm^2)	22,466 a[y]	21,334 a	4,295 a	4,019 a
Leaf number (no.)	1,178 a	1,193 a	328 a	363 a
Shoot fresh mass (g)	1,417 a	1,452 a	344 a	359 a
Shoot dry mass (g)	158 a	165 a	31 a	32 a

[z]W = with a nutrient solution replacement every two weeks; W/O = without a nutrient solution replacement. Growth data are cumulative of four plants per replicate hydroponic system (n = 8).

[y]For each environment, means within row followed by the same letter are not different based on Student's *t* test at $P \leq 0.05$.

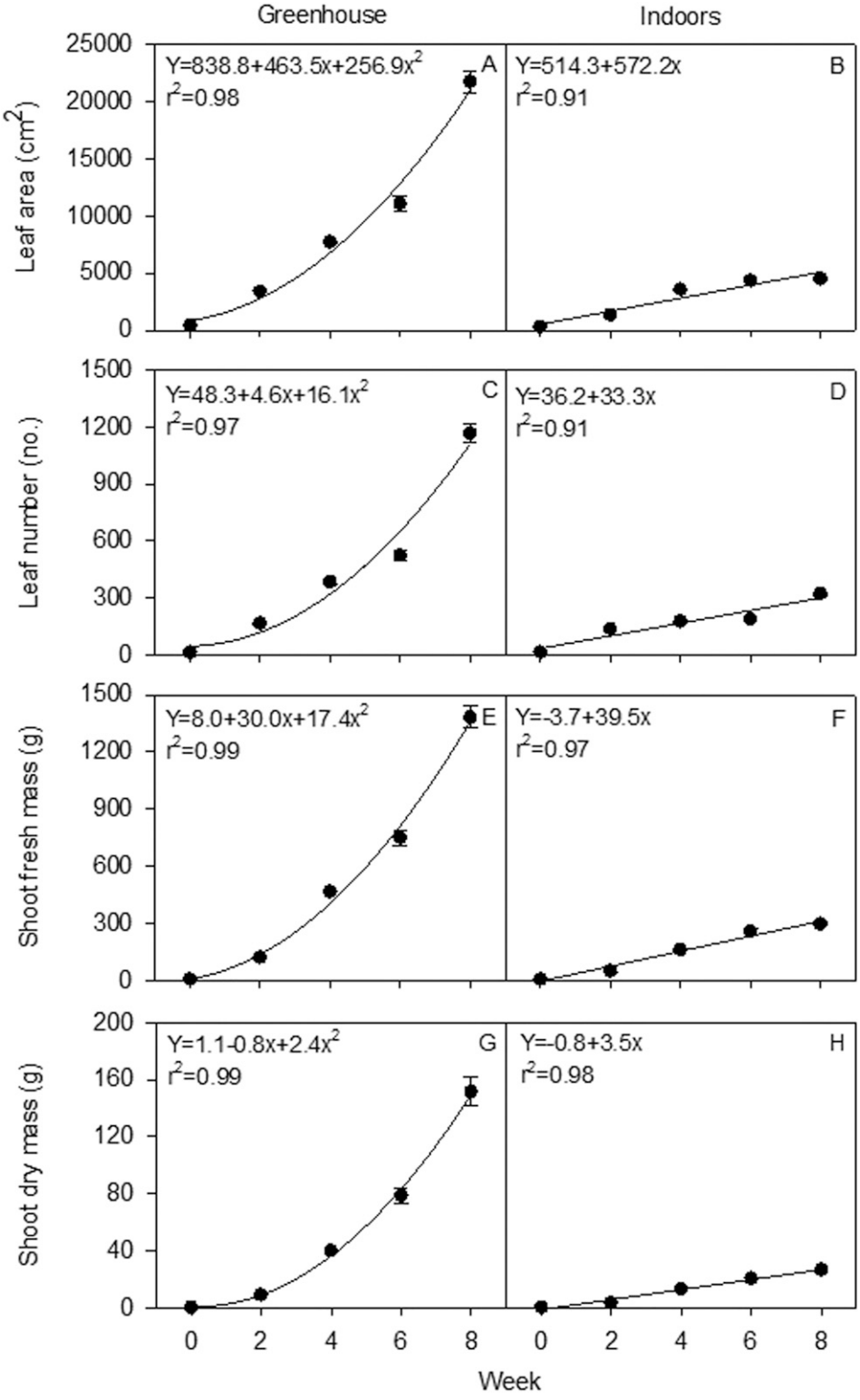

Fig. 1. Growth parameters for basil grown in a greenhouse (**A**–**G**) or indoor (**B**–**H**) environment with a nutrient solution replacement every 2 weeks at different harvest dates (0, 2, 4, 6, and 8 weeks). Black circles represent the average mean ± SE for two experimental runs. Data are cumulative for four plants per replicate hydroponic system per environment (n = 6 to 8 replicate systems).

be the result of lower dry mass (Table 1) for indoor-grown plants despite higher tissue nutrient concentration (Table 4). The trend in N uptake over time with plants grown using the W treatment allows comparison against N supplied in fertilizer (Fig. 4). After week 4, nearly all the N applied was taken up by plants grown in the greenhouse (Fig. 4A), resulting in a highly depleted solution (Table 3). In contrast, plants grown indoors took up less than 50% of the N provided (Fig. 4B).

Discussion

Our data indicate that within each environment, the two solution management treatments evaluated in our study did not affect basil growth, development, or overall yield (Table 1). This was unexpected, as guidelines for commercial basil production typically recommend replacing the nutrient solution every 1 to 2 weeks (David et al., 1996; Jones, 2005; Kang and van Iersel, 2002; Lykas et al., 2006; Samarakoon et al., 2006; Spensley et al.,

Table 2. Final nutrient solution parameters measured for basil plants grown inside a greenhouse or indoor environment for 8 weeks under one of two nutrient solution management treatments.

	Greenhouse		Indoors	
Nutrient solution parameters	W[z]	W/O	W	W/O
Frequency of refill water applications	22.0 a[y]	22.0 a	7.0 a	7.0 a
Total refill water applied (L)	37.6 b	41.3 a	12.5 a	10.7 b
Final electrical conductivity (dS·m^{-1})	0.6 b	1.1 a	1.1 b	4.8 a

[z]W = with a nutrient solution replacement every two weeks; W/O = without a nutrient solution replacement. Data represent average values measured for each replicate hydroponic system with four plants (n = 8).
[y]For each environment, means within row followed by the same letter are not different based on Student's *t* test at $P \leq 0.05$.

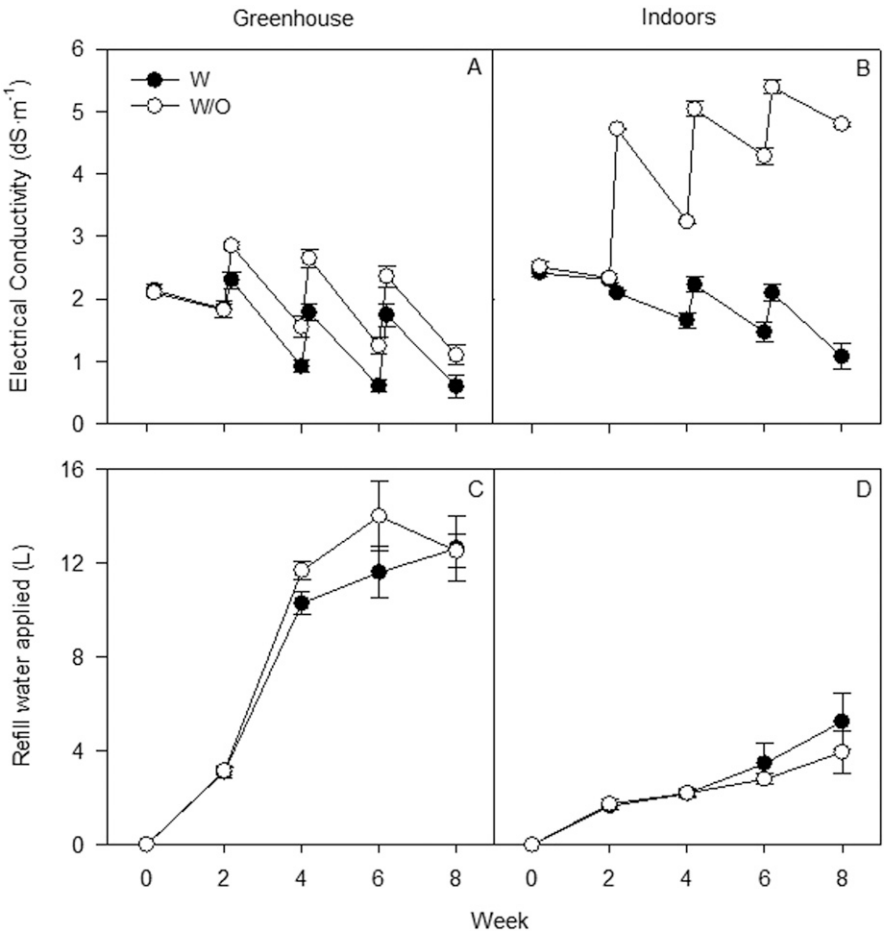

Fig. 2. Electrical conductivity (**A**–**B**) and refill water applied over time (**C**–**D**) for hydroponic basil grown with (W) or without (W/O) a nutrient solution replacement every 2 weeks. Means ± SE are represented by black and white circles for the W and W/O treatment, respectively (n = 8).

1978). Although optimal EC for basil production can range from 0.5 to 1.6 dS·m^{-1} (Dunn and Singh, 2016; Moya et al., 2014; Owen et al., 2018; Somerville et al., 2014), we found that a higher EC (up to 5.5 dS·m^{-1} for the W/O treatment indoors) did not affect final growth and yield of hydroponic basil grown for 8 weeks (Table 2, Fig. 2). In addition, fluctuations in solution EC did not negatively affect basil growth regardless of sudden increases after biweekly fertilizer additions or decreases from periodic refill water dilution (0.44 dS·m^{-1}). Similar to our results, Walters and Currey (2018) found that solution EC ranging from 1.3 to 3.1 dS·m^{-1} did not affect SFM of basil. Walters and Currey (2018) reported that regardless of the effect of nutrient solution EC on tissue nutrient concentration, growth of sweet basil was unaffected by different EC treatments ranging from 0.5 to 4.0 dS·m^{-1}.

Although up to a point, EC has been shown to have a small effect on SFM of basil, commercial growers are likely to maintain EC within the recommended ranges of production, as their goal is to maximize yield to increase profits. However, production goals for indoor gardeners may differ from those of commercial growers, considering that indoor gardeners seek to be actively involved in the growing and harvesting process and may be satisfied with small harvests for their personal use (Gao et al., 2009; Paz et al., 2019). Therefore, EC in hydroponic systems used for indoor gardening of basil may not need to be maintained within the recommended ranges for commercial production, as the lack of treatment differences in our study suggest that frequent solution replacements are unnecessary (Table 2). In addition, minimizing the frequency of solution replacement intervals indoors could reduce the required fertilizer to grow plants. Reducing inputs such as time and fertilizer used to maintain a hydroponic production system could increase the appeal to indoor gardeners, as the necessary interventions related to plant care would be limited (Resh, 2015; USDA, 1978).

Growth over time differed greatly between the two environments (Fig. 1). Considering that plant growth is regulated in part by environmental parameters, and the effect of these parameters is cumulative, the rate at which plants grew and developed was much faster in the greenhouse than indoors due to higher temperatures (Walters and Currey, 2019), light availability (Beaman et al., 2009; Solis-Toapanta and Gómez, 2019), water consumption, and nutrient uptake, among other factors. Furthermore, as leaf size and radiation capture increased quadratically, plants in the greenhouse had a higher capacity to make use of the aforementioned conditions compared with plants grown indoors, which grew at a much slower rate (Bugbee, 2016; Taiz and Zeiger, 2006).

Greenhouse-grown plants consumed five times more water than those grown indoors (Fig. 2A and B). Accordingly, reservoirs of plants grown indoors were only refilled with water seven times during the experiment, whereas those of plants grown in the greenhouse required 22 refill water applications (Table 2). Morano et al. (2017) showed that for basil plants grown in a greenhouse, water use was highest during warmer temperatures, illustrating how temperature influences the rate at which basil plants grow and consume inputs. In our study, the average temperatures in the greenhouse and indoors for the 8-week production cycle were 29/24 °C day/night and a constant 21 °C, respectively. Temperature is widely known to affect water loss in plants as an indirect response to physiological responses such as transpiration (Chang et al., 2005). In addition, warmer temperatures typically increase leaf unfolding rate and leaf area, a trend that corresponds with the differences measured for leaf number and leaf area in our study (Fig. 1A–D). Furthermore, the difference between the day and night temperature (DIF) may have been partly responsible for the growth responses measured in both environments, because DIF regulates internode length, which indirectly affects radiation capture of inner leaves and therefore influences plant growth and

Table 3. Final nutrient concentration of a hydroponic solution used for basil plants grown inside a greenhouse or indoor environment for 8 weeks under one of two nutrient solution management treatments.

	Nutrient concn (mg·L^{-1})										
Environment	N	P	K	Ca	Mg	S	Fe	Mn	B	Cu	Zn
Greenhouse											
W[z]	0.4 a[y]	1.9 a	1.4 a	57.0 b	53.2 b	99.5 b	1.49 b	0.07 a	0.08 b	0.11 b	0.15 b
W/O	0.0 b	2.5 a	1.3 b	126.7 a	111.2 a	233.2 a	3.25 a	0.17 a	0.32 a	0.39 a	0.31 a
Indoors											
W	35.9 b	27.8 b	88.5 b	73.8 b	49.1 b	26.4 b	1.57 b	0.01 b	0.19 b	0.16 b	0.11 b
W/O	505.3 a	178.7 a	691.8 a	390.1 a	184.6 a	91.5 a	5.26 a	2.16 a	1.08 a	0.55 a	0.48 a

[z]W = with a nutrient solution replacement every 2 weeks; W/O = without a nutrient solution replacement. Solution data represent values collected from four replicate hydroponic systems, each with four plants within one experimental run (n = 4).
[y]For each environment, means within column followed by the same letter are not different based on Student's *t* test at $P \leq 0.05$.

Table 4. Final tissue nutrient concentration for basil plants grown inside a greenhouse or indoor environment for 8 weeks under one of two hydroponic nutrient solution management treatments.

	N	P	K	Ca	Mg	S	Fe	Mn	B	Cu	Zn
Environment	----------%----------						----------ppm----------				
Greenhouse											
W[z]	2.2 b[y]	0.7 b	3.4 a	1.5 a	0.5 a	0.2 a	70 a	82 a	24 a	7 a	22 a
W/O	2.9 a	0.9 a	3.9 a	1.5 a	0.5 a	0.2 a	65 a	93 a	25 a	7 a	26 a
Indoors											
W	5.9 a	1.0 a	6.9 a	1.7 a	0.6 a	0.3 a	135 b	123 a	43 a	16 a	59 a
W/O	6.2 a	1.0 a	6.9 a	1.7 a	0.6 a	0.3 a	196 a	121 a	41 a	23 a	62 a
Survey ranges[x]	4–6	0.6–1	1.6–2.1	1.3–2	0.6–1.0	0.2–0.6	75–200	30–150	25–60	5–10	30–70

[z]W = with a nutrient solution replacement every 2 weeks; W/O = without a nutrient solution replacement. Data represent average values measured from each replicate hydroponic system with four plants (n = 8).
[y]For each environment, means within column followed by the same letter are not different based on Student's *t* test at $P \leq 0.05$.
[x]Survey ranges from field-grown basil plants (Bryson et al., 2014).

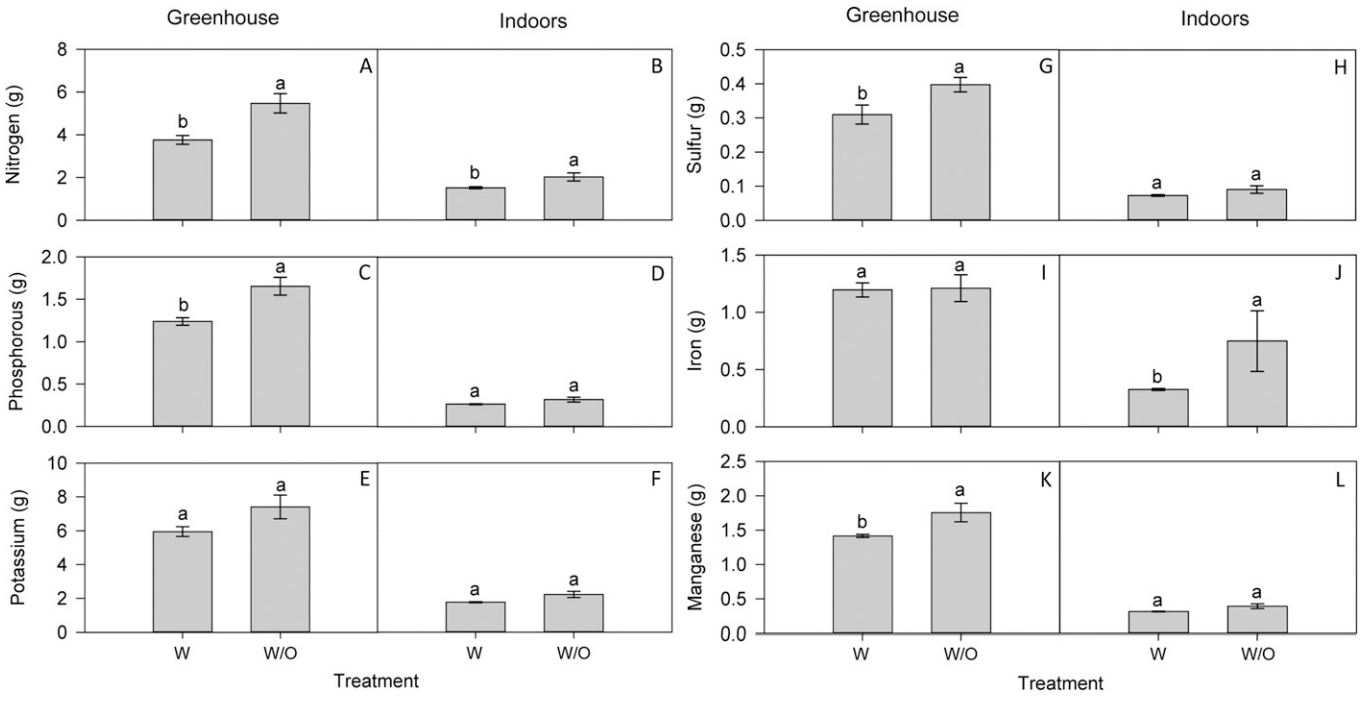

Fig. 3. Nutrient uptake measured for basil plants grown inside a greenhouse (**A**, **C**, **E**, **G**, **I**, **K**) or indoor (**B**, **D**, **F**, **H**, **J**, **L**) environment for 8 weeks with (W) or without (W/O) a nutrient solution replacement every 2 weeks. Data represent average means ± SE from pooled samples of four plants per replicate hydroponic system (n = 6 to 8 replicate systems). For each environment, means within graph with the same letter are not different based on Student's *t* test at $P \leq 0.05$.

biomass production (Table 1, Fig. 1E–H) (Erwin et al., 1989; Erwin and Heins, 1995). Plants grown in the greenhouse experienced a positive DIF, and those grown indoors were exposed to a DIF of zero. Accordingly, Frąszczak et al. (2011) found that 'Wala' and 'Kasia' basil plants grown with a positive DIF produced more fresh and dry mass than those grown under a DIF of zero. Higher transpiration rates and more leaf area from larger plants transpiring under the warmer temperatures are likely responsible for the differences measured in water consumption between both environments.

The EC measurements fluctuated throughout the production cycle, primarily because of sudden changes after biweekly fertilizer additions, or from solution dilution after adding refill water (Fig. 2A and B). The higher growth rate in the greenhouse enabled EC levels to remain within the recommended

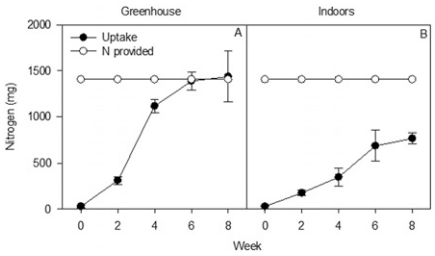

Fig. 4. Nitrogen uptake over time measured for basil plants grown inside a greenhouse (**A**) or indoor (**B**) environment with a nutrient solution replacement every 2 weeks. Data represent average means ± SE from pooled samples of four plants per replicate hydroponic system for each environment for the first experimental run (n = 4). Black circles represent the means of nitrogen uptake ± SE, and white circles represent the total amount of fertilizer provided every 2 weeks after biweekly solution replacements.

ranges for commercial production (Fig. 1) (0.5 to 1.6 dS·m^{-1}; Moya et al., 2014; Somerville et al., 2014). In contrast, the lower growth rate indoors resulted in higher-than-recommended EC levels (Table 2, Fig. 2). Solution EC may have affected water uptake, whereby the total refill water volume applied was lower for the W/O treatment than the W treatment. In addition, leaf area was generally lower in the W/O treatment, reducing water demand for transpiration and possibly leading to EC values above the recommended ranges for commercial production (>1.6 dS·m^{-1}). Similar to our findings, Savvas et al. (2007) reported that an increase in solution EC reduced water uptake of basil. Chartzoulakis and Klapaki (2000) suggested that reductions in water uptake are likely an adaptation response to salinity through which plant leaves close their stomata to decrease transpirational water loss, which contributes to an increase in water-use efficiency.

Published survey ranges for soil-based basil plants grown outdoors from Bryson et al. (2014) provide a baseline for the interpretation of our tissue nutrient analyses data. For plants grown in the greenhouse, tissue concentration for N, magnesium, and iron were below the recommended ranges of 4% to 6%, 0.6% to 0.1%, and 75 to 200 ppm, respectively (Table 4). We observed that plants grown in the greenhouse were mildly chlorotic, which is an indication of deficiency of those specific nutrients. In contrast, tissue concentration for N, P, and all micronutrients of plants grown indoors approximated the upper limits of the survey ranges, which is most likely attributed to the reduced growth rate indoors compared with the greenhouse. Moreover, tissue concentration analyses indicated that greenhouse- and indoor-grown plants had approx. 4% and 7% of K, respectively, which were above the recommended rate. It is likely that the high K concentration measured in the tissue is a result of the higher K availability in the solution, which can be explained by the biweekly addition of potassium carbonate and potassium silicate used to raise solution pH. Similar to our findings, Walters and Currey (2018) reported that luxury consumption of K occurs due to increased K concentration in the solution.

Although the supply of N was constant throughout the experiments (≈1400 mg every two weeks), N uptake rates varied between environments (Fig. 4). After week 4, N uptake by greenhouse-grown plants equaled the total biweekly supply. In addition, final tissue N concentration was below the survey range, suggesting that the N concentration supplied in our study limited plant growth in the greenhouse (Table 4). In contrast, N supply was enough for plants grown indoors, as N uptake did not surpass the N provided. Although plants in our study showed no severe signs of N deficiency, greenhouse-grown plants could have benefited from an increase in N concentration after week 4. However, the fertilizer rates used in our study seem to be appropriate for indoor gardening, as indicated by the general trends measured in the final tissue nutrient concentration, which regardless of treatment, were within the survey ranges for optimal production and plant health. This is an important consideration, as indoor gardeners tend to follow guidelines for commercial production, which are typically geared toward maximizing plant growth and yield. However, our results indicate that fertilizer recommendations for greenhouse production may not be appropriate for indoor gardening, as growth rates are expected to be different. Reducing the need for fertilizer application may increase the appeal for indoor gardening, as resource conservation (e.g., less fertilizer input) and environmental stewardship (e.g., less disposal of nutrient-rich water) can be attractive features among those interested in gardening activities (Strunk and Lang, 2019).

Other important considerations for indoor gardeners include raw water quality parameters such as EC, pH, alkalinity, and the specific presence of chloride, sulfate, boron, nitrate, and sodium, among others, that are commonly monitored when using hydroponic production systems (Bauder et al., 2011). Commercial hydroponic growers typically test raw water quality before formulating nutrient solutions to determine any necessary treatment requirements (e.g., reverse osmosis and water softener) (Heidekamp and Lemley, 2005; Nelson, 2012). Nonetheless, without any adjustments, municipal water, which is the most likely water source to be used by indoor gardeners, may have a pH, EC, or alkalinity outside recommended production ranges. For example, U.S. municipal water has a pH that ranges between 7.0 and 8.5 due to carbonates and bicarbonates that help minimize the rate of pipe corrosion in city water distribution lines (WHO, 2011). Moreover, approximately 85% of U.S. cities are supplied with water that has high concentrations of sulfide, sodium, heavy metals or, more specifically, calcium and magnesium, and often rely on hard water (i.e., high content of dissolved minerals; 120 to 180 ppm) (Heidekamp and Lemley, 2005). Although the quality of municipal water may not be optimal for plant production, it is unlikely that indoor gardeners will follow commercial water treatment guidelines, as it could require a significant and likely unnecessary investment. In addition, purchasing instruments and supplies to constantly monitor the nutrient solution (e.g., pH and EC meters) represents a cost for indoor gardeners, which also entails the could-be-considered burdensome task of monitoring the nutrient solution. Therefore, it is important for fertilizers and other nutrient solution management supplies for indoor hydroponic gardening to be functional in a wide range of locations to account for varying water qualities, as they will directly impact plant growth and consumer success.

In conclusion, in both environments, nutrient solution management treatments had no effect on basil yield. Although fresh and dry mass indoors was approximately ¼ of that measured in the greenhouse, indoor gardeners could produce over 340 g of fresh basil in an 8-week production cycle without having to replace the nutrient solution, assuming that environmental conditions and production practices are similar to the ones used in this study. Overall, the production environment had large effects in plant growth and development, refill water applied, frequency of refill water applications, and nutrient uptake. Therefore, recommendations for solution management and fertilization strategies could be tailored to the environmental conditions and production needs of indoor gardeners. For example, considering that EC increased in the solution of indoor-grown plants under W/O, an appropriate strategy using this treatment would require reducing fertilizer inputs indoors. Based on the increasing interest in indoor gardening, research evaluating low-input practices to successfully grow edible plants indoors is needed, including responses of other plant species, cultivars, and water qualities.

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