Tomato Seedling Performance in Five Commercial Organic Growing Media with and without Supplemental Fertilizer

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Abstract. **Commercially available growing media permitted for use in certified organic production differ substantially in quantity and availability of essential macronutrients. Nutrient availability from fertilizers applied during production will depend on chemical, biological, and physical characteristics of both media and fertilizers; therefore, best practices for fertilizing seedlings are likely to differ. This study evaluated tomato (*Solanum lycopersicum* L.) emergence, seedling growth, and posttransplant performance when grown in five organic growing media with and without supplemental fertilizer during transplant production in three diverse locations. A 5N–0.88P–3.32K–3Ca (5–2–4) dry fertilizer was tested in all media, and a liquid 3N–0.88P–2.49K (3–2–3) fertilizer was tested in two media. Fertilizer improved growth of seedlings in two media that did not contain compost, but not consistently in compost media. Incorporation of dry fertilizer before seeding inhibited emergence, especially in compost media with high electrical conductivity (EC). In noncompost media, liquid fertilizer improved growth more when application began early. Both fertilizers increased media EC and altered pH, with larger changes in noncompost media. Without fertilizer, nitrogen (N) and potassium (K) were deficient in plant tissue after 4 to 5 weeks. Fertilizer increased N and K concentrations, especially in noncompost media, but only applications of liquid fertilizer near the end of transplant production consistently prevented N deficiency. Four weeks after transplanting to the field, plants fertilized as seedlings were larger than unfertilized plants, especially when grown in noncompost media, and they had more flower clusters and set fruit earlier. At one location where yield was measured, early yield of seedlings grown in noncompost media was greater when they were fertilized. They also produced more tomatoes, but the average fruit size was smaller. In compost media, fertilizer had inconsistent effects on flowering, fruit set, and yield. Based on this work, for media without compost and low in nutrients, fertilization is recommended beginning early in seedling production. For compost media with high initial EC, delaying fertilizer application for approximately 3 weeks is recommended. More research is needed to identify best management practices related to fertilizer rates, application methods, and timing. Development of methods to assess the need for fertilization that can be implemented on farms will be valuable to improving organic transplant production.**

Healthy transplants are important for successful organic vegetable production. Previous work has shown that tomato seedling performance differs among growing media suitable for use in certified organic production, and the nitrogen (N) supply seems to be responsible (Maynard et al. 2024). Recommendations for organic transplant production suggest incorporating nutrients into the growing medium or providing supplemental fertilizer during seedling production as needed (Biernbaum 2013; Greer and Adam 2005; Grubinger 2023; Wander 2009). To ensure grower success, more specific information about incorporated and supplemental nutrient sources and rates would be useful. Because organic media differ in nutrient content and availability, growers also need guidance regarding whether supplemental fertilizer is likely to be needed for the media they use.

Previous studies have confirmed that a variety of nutrient sources suitable for use in organic production can be used successfully in containers and, more specifically, for production of vegetable transplants (Burnett et al. 2016; Rogers 2017; Stewart-Wade 2020a, 2020b). Solid fertilizers incorporated at 0.59 to 1.7 $kg \cdot m^{-3}$ (0.25 to 1.1 lb/yard^3) of N generally have resulted in acceptable plant growth without injury to the crop. However, these reviews also document that, depending on the rate and specific nutrient source, fertilizers mixed into growing media can reduce plant growth and seed germination can be inhibited (Diaz-Perez et al. 2017). Authors attribute differences in response to variations in rates of N transformation, the presence of phytotoxic compounds, and influence on electrical conductivity (EC) and pH of the growing media. These parameters can be difficult for growers to predict.

Studies that compared organic fertilizers for vegetable transplants have investigated different treatments in a single growing medium. Growing media differ in the initial pH, EC, nutrient content, and biological and physical characteristics. These factors are likely to influence the effects of organic fertilizers on crops. For example, Frerichs et al. (2020) demonstrated the importance of media characteristics to shaping the response to applied fertilizer. They showed that lowering the initial media pH and priming biological activity by incubating media with compost before planting could partially counteract negative effects of a high fertilizer application rate on basil (*Ocimum basilicum* L.) by reducing the conversion of mineralized ammonium to toxic ammonia. In another study, Cannavo et al. (2022) demonstrated that N mineralization dynamics of organic fertilizers varied among four organic growing media; because variation in N mineralization would affect plant growth, they recommended that combinations of growing media and fertilizers should be tested using plant growth experiments.

This study was conducted to further investigate how different combinations of growing media and fertilizer type can influence seedling growth. We used five commercially available growing media and amended these with fertilizer that could provide major macronutrients in ratios that approximate plant use because previous work with these media suggested that N, and possibly potassium (K), were limiting factors (Maynard et al. 2024). Specific research questions included the following: 1) How do the fertilizers influence tomato (*Solanum lycopersicum* L.) germination, growth during transplant production, and early growth and yield potential after the seedlings grown under different treatments were planted in the field? and 2) Do the effects of fertilizer differ among media? To understand the basis for these effects, measurements of growing media pH, EC, and plant tissue nutrient content were collected during some trials. The findings can be used for planning supplemental fertilization during organic tomato transplant production considering characteristics of the growing medium in use.

Materials and methods

Five greenhouse trials were conducted at the following Indiana locations in 2019 and 2020: two at Pinney Purdue Agricultural Center, Wanatah, IN, USA (PP1 and PP2), two at Horticulture and Landscape Architecture Plant Growth Facility, West Lafayette, IN, USA (PS1 and PS2), and one at Southwest Purdue Agricultural Center, Vincennes, IN, USA (SW) (Table 1). Each trial had a randomized complete block design with four replications and 12 treatments comprising five growing media with and without solid fertilizer plus two of the media with liquid fertilizer. In each trial, the experimental unit was a standard 72-cell plug tray with square cells 3.86 cm (1.52 inches) across and 5.72 cm (2.25 inches) deep with a volume of 59.0 cm^3 (3.60 $inches^3$) (Standard Plug Tray PL72; T.O. Plastics, Inc., Clearwater, MN, USA) cut in half to form a square flat containing 36 cells. Plants on the edge of the flat were included in emergence counts; otherwise, they were not used for data collection. Details of greenhouse environmental conditions and seeding dates are provided in Table 1.

Growing media. Growing media approved for certified organic production were used in the trials: Premium Flower 201 (M201; Morgan Composting, Sears, MI, USA); Promix MP Organik (PMPO; Premier Tech Horticulture, Quakertown, PA, USA); Seed Catapult (SCOE; Ohio Earth Food, Hartville, OH, USA); Sunshine No. 1 Natural and Organic (SUN1; Sun Gro Horticulture, Agawam, MA, USA); and Fort Light (VCFL; Vermont Compost, Montpelier, VT, USA). We intentionally chose products that contained compost (M201, SCOE, VCFL) and those that did not (PMPO and SUN1) because prior research showed significant differences in crop performance with compost and noncompost media (Maynard et al. 2024). Chemical characteristics of the media based on the saturated media extract (SME) analysis and compost analysis procedures conducted by a commercial laboratory are provided in Table 2.

Fertilizers. Treatments included each growing medium with and without a dry fertilizer derived from composted turkey litter, feather meal, and sulfate of potash and containing 5N–0.88P–3.32K–3Ca (5–2–4; Suståne Natural Fertilizer, Cannon Falls, MN, USA). In two additional treatments, a liquid fertilizer derived from poultry manure containing 3N–0.88P–2.49K (3–2–3; Envirokure, Philadelphia, PA, USA) was applied to tomatoes growing in PMPO and VCFL. These two media were chosen for the liquid fertilizer treatments to represent a noncompost medium and a compost medium. Each fertilizer was applied at the same rate to all media. The rate was calculated to contain enough N for a 4% concentration in aboveground plant tissue on a dry weight basis at the end of transplant production. This concentration was more than adequate (Wilcox 1993), and the dry weight of 1 g/plant used in the calculation was based on the size of large transplants in a previous study (Maynard et al. 2024).

In Expt. 1 (PP1, PS1, and SW), the dry fertilizer was mixed by hand into media at a rate of 15 $kg \cdot m^{-3}$ [25 lb/$yard^3$ providing (in $kg \cdot m^{-3}$) 0.75 N, 0.13 phosphorus (P), 0.50 potassium (K), and 0.45 calcium (Ca)] before the media was moistened and put into flats, and the liquid fertilizer was applied in a solution of 500 $mg \cdot L^{-1}$ (ppm) N beginning 8 to 11 d after seeding (DAS). Application of liquid fertilizer continued approximately weekly until 3000 mL [116 fl oz, providing (in $kg \cdot m^{-3}$) 0.78 N, 0.23 P, 0.65 K] had been applied or the experiment was ended. A sample of 5–2–4 analyzed by a commercial laboratory (Midwest Laboratories, Omaha, NE, USA) had pH of 6.19, salt index of 16, total N level of 6.05%, ammonium-N level of 0.36%, undetectable nitrate-N, available P level of 1.6%, soluble K level of 3.93%, Ca level of 3.83%, magnesium (Mg) level of 0.73%, sodium (Na) level of 0.38%, sulfur (S) level of 2.32%, iron (Fe) level of 0.259%, undetectable boron (B), chloride (Cl) level of 0.52%, and carbon (C) level of 30.16%. A sample of the fertilizer solution that was sent to a commercial laboratory (A and L Great Lakes Laboratories, Fort Wayne, IN, USA) for analysis had a pH of 8.3, EC of 3.93 $dS \cdot m^{-1}$, and the following (in $mg \cdot L^{-1}$): nitrate-N, 383; ammonium-N, 44.6; P, 7.0; K, 502; Ca, 74; Mg, 24; Na, 581; S, 220; Fe, 0.07; B, 0.09; molybdenum (Mo), 0.02; silicon (Si), 5; Cl, 37; and alkalinity [calcium carbonate ($CaCO_3$) equivalent], 425. Preliminary results of Expt. 1 showed that fertilizer affected emergence; therefore, during Expt. 2 (PP2 and PS2), the same rates of fertilizer were used, but applications were delayed. The dry fertilizer was sprinkled on the surface of the growing media in two applications: at 7 and 10 DAS (first application) and at 21 and 26 DAS (second application) at PP2 and PS2, respectively. The liquid fertilizer was applied daily beginning 22 and 26 DAS at PP2 and PS2, respectively, until 3000 mL of the 500 ppm N solution had been applied.

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Table 1. Characteristics of trials comparing growth of tomato in growing media approved for use in organic production with and without supplemental fertilizer.

	Pinney Purdue Agricultural Center (PP)	HLA Plant Growth Facility and Purdue Student Farm (PS)	Southwest Purdue Agricultural Center (SW)
City	Wanatah	West Lafayette	Vincennes
Latitude, longitude	41.4427754°N, −86.9312414°W	40.420540°N, −86.914152°W	38.739094°N, −87.487703°W
Greenhouse covering	Double poly	Double poly	Double poly
Daily temp, mean ± *SD*, °C[i]			
Trial 1	23.0 ± 2.6	No data	23.2 ± 3.3
Trial 2	26.8 ± 2.5	21.2 ± 0.7	No trial 2
Daily light integral, mean ± *SD*, $mol\cdot m^{-2}\cdot d^{-1}$			
Trial 1	21.2 ± 11.0	No data	No data
Trial 2	24.1 ± 8.4	15.5 ± 6.55	No trial 2
Seed date			
Trial 1	18 Mar 2019	3 Jun 2019	28 Mar 2019
Trial 2	3 Jun 2019	6 Mar 2020	No trial 2
Transplant date	3 Jul 2019	2 Jul 2019	6 May 2019
Soil characteristics[ii]			
Type	Tracy sandy loam[iii]	Mahalasville-Treaty complex[iv]	Alvin fine sandy loam[v]
Organic matter (%)	2.4	4.8	0.9
pH	6.2	No data	6.2
Phosphorous (ppm)	93	No data	50
Potassium (ppm)	162	No data	83
Magnesium (ppm)	190	No data	80
Calcium (ppm)	700	No data	600

[i] *SD* = standard deviation; (°C × 1.8) + 32 = °F.
[ii] Soil chemical test performed by A and L Great Lakes Laboratories, Fort Wayne, IN, USA, and reported as the Bray-1 equivalent for phosphorous and the ammonium-acetate equivalent for other elements.
[iii] Mixed, active, mesic Ultic Hapludalf.
[iv] Mixed, superactive, mesic Typic Argiaquoll.
[v] Mixed, superactive, mesic Typic Hapludalf.

Emergence and seedling performance. Flats were filled with media, seeded with tomato (*Solanum lycopersicum* cv. Big Beef; Johnny's Selected Seeds, Winslow, ME, USA), and watered until water leached from holes in the bottom of the cells (hereafter referred to as to run-through). Thereafter, flats were hand-watered as needed based on visual observation to maintain moderate moisture in the growing media. At SW, flats were on germination mats set to maintain 26.7 °C (80 °F) until 90% of seeds germinated. At other locations, flats were on greenhouse benches with no supplemental heat. Emergence was recorded daily from initiation until at least 90% of seedlings had emerged.

Plant growth was measured three times during seedling production: at 14 to 17 DAS and then at 4-d to 12-d intervals. On each date, three randomly selected plants were cut at the soil level; thereafter, leaves per plant, combined fresh weight, and combined dry weight

Table 2. pH, electrical conductivity (EC), total nitrogen, ammonium-nitrogen, nitrate-nitrogen, and plant mineral nutrients in five growing media before planting tomatoes.

Medium[i]	pH[ii]	EC[ii]	Total nitrogen[iii]	Ammonium-nitrogen[iii]	Nitrate-nitrogen[ii]	Phosphorus[ii]	Potassium[ii]	Calcium[ii]	Magnesium[ii]	Sodium[ii]
		$(dS\cdot m^{-1})$[iv]	(%)				$(mg\cdot L^{-1})$[v]			
M201	6.05	4.48	0.98	176	218	10	682	525	121	155
PMPO	4.75	0.66	0.98	12	1	23	98	9	4	40
SCOE	7.10	1.52	0.56	202	1	43	160	48	13	60
SUN1	5.80	1.23	0.68	1	42	26	60	124	40	75
VCFL	6.00	3.88	1.42	76	246	32	504	411	82	222

[i] M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not contain compost.
[ii] pH measured in 1:2 v/v mix of medium and deionized water; others were measured in saturated media extract with DTPA (diethylenetriamine penta-acetic acid) (Warncke 1998) by A and L Great Lakes Laboratories, Fort Wayne, IN, USA.
[iii] Total nitrogen on a dry weight basis and ammonium-nitrogen determined by A and L Great Lakes Laboratories, Fort Wayne, IN, USA, following the methods of US Composting Council 2015, using different samples than other measurements.
[iv] $1\ dS\cdot m^{-1}$ = 1 mmho/cm.
[v] $1\ mg\cdot L^{-1}$ = 1 ppm.

after drying at 55 to 60 °C (131 to 140 °F) were recorded. At the final growth measurement, plant height and diameter of the stem below the cotyledons were measured on the sampled plants. At SW, a fourth measurement was performed at 35 DAS.

The final plant samples from PP1 and PP2 and the second and final samples from PS2 were sent to a commercial laboratory (Brookside Laboratories, New Bremen, OH, USA) to determine the nutrient concentration following methods described for N and minerals by Miller et al. (2013).

MEDIA MEASUREMENTS. The EC and/or pH of growing media were measured twice in most trials: between 9 and 12 DAS and between 24 and 36 DAS. Flats were watered to run-through, and sampling began 30 to 60 min later. At SW, values were determined in one cell per experimental unit using an ion-sensitive field-effect transistor for pH (Wireless ISFET pH probe; Spectrum Technologies, Aurora, IL, USA). At PP and PS, three cells per experimental unit were sampled using a modification of the pour-through (PT) method described by Wright (1986). Five to 15 mL (0.19–0.58 fl oz) of distilled or deionized water was poured into a cell, the leachate was collected, and EC and pH were measured. Measurements of each experimental unit were averaged to evaluate treatment effects.

FIELD PERFORMANCE. Tomatoes from one greenhouse trial at each location (PP2, PS1, and SW) were transplanted to the field. Each field trial was arranged as a continuation of the associated greenhouse trial and had a randomized complete block design with four replications and 12 treatments. An experimental unit consisted of six plants at PP and SW and four plants at PS. At PP and PS, the field trials were located in organically managed but noncertified experimental areas. At SW, the trial was in a conventionally managed area that received no synthetic inputs during the trial other than plastic mulch. No fertilizers were applied to the soil at any location before transplanting. Seedlings were transplanted by hand 0.46 m (18 inches) apart in a single row on beds covered with 1.2-m-wide (width, 4 ft) black plastic mulch [PP: 25 µm (1 mil) embossed; Trickleez Irrigation, Inc., St. Joseph, MI, USA; SW: 20 µm (0.8 mil); Ginegar Plastic, Inc., Santa Maria, CA, USA] or with 1.8-m-wide (6-ft-wide) black woven weed mat (DeWitt Company, Sikeston, MO, USA) at PS. Beds were 3 m (10 ft) on center at PP, 0.9 m (3 ft) at PS, and 1.8 m (6 ft) at SW. At PS and SW, plants were supported with a Florida weave trellis. At PP, plants were not supported or pruned. Plants were watered in by hand at transplanting and then irrigated as needed through a single line of drip tape under the mulch (Rivulis Ro-drip; Rivulis Irrigation Inc., San Diego, CA, USA). At PP and PS and at SW, 30-cm and 20-cm (12-inch and 8-inch) emitter spacing [0.9 $L \cdot h^{-1}$ per emitter at 55 kPa (0.24 gal/h per emitter at 8 psi)] were used, respectively.

Vegetative growth was evaluated 14 d after transplanting (DAT) and 28 DAT at PP2, 16 DAT, 21 DAT, and 28 DAT at PS1, and 11 DAT, 23 DAT, 29 DAT, and 37 DAT at SW by counting the number of fully expanded leaves on the main stem, measuring stem diameter just below the cotyledonary node, and measuring height from soil to the main stem growing point for each plant. On the final growth measurement date at PP2 and PS1, the number of buds, open flowers, fruit set, and aborted buds or flowers on the first main stem cluster, and fresh and dry weights were determined for three randomly selected plants per plot. Additionally, at PP2, the total number of clusters with open flowers or fruit were determined for three randomly selected plants per plot.

At SW, ripe fruit was harvested twice weekly from 8 Jul through 5 Aug, and the number and weight were recorded. Early yield and fruit number were calculated by summing the first three harvests. Average weight per fruit was calculated over the entire harvest period.

DATA ANALYSES. Maximum emergence, days to 50% emergence, and emergence uniformity were estimated for each experimental unit by fitting the sigmoid equation:

$$y = a/[1+e^{-(x - b)/c}] \qquad [1]$$

where y = % emergence, x = days after seeding, a = maximum emergence, b = days to 50% emergence, and c is related to the steepness of the sigmoid curve; a smaller value indicated a steeper curve and, therefore, more uniform emergence. The nonlinear platform of JMP Pro software (version 14, 15, or 16; SAS Institute Inc., Cary NC, USA) was used to estimate parameters.

Seedling fresh and dry weights for each experimental unit were used to estimate parameters *a1*, *b1*, and *c1* for the following equation:

$$\ln(y) = a1 + b1\ x1 + c1\ x2 \qquad [2]$$

where x1 and x2 are orthogonalized values of x (days after seeding) and x^2 and y is fresh weight + 0.01 or dry weight + 0.001; the fractional amounts were added to allow inclusion of aboveground weights of 0 on day 0. Parameter *a1* represents the intercept, parameter *b1* represents the slope or overall relative growth rate, and parameter *c1* represents the departure from a constant relative growth rate over the course of the experiment, with negative values indicating slowing of the relative growth rate. The fit model standard least squares platform of JMP Pro software (version 14, 15, or 16) was used to estimate parameters.

An analysis of variance (ANOVA) was performed separately for each trial to evaluate effects of treatments on responses. Fixed effects included replication and treatment. Preplanned single degrees of freedom contrasts were constructed to evaluate the main effects of each fertilizer averaged across media, of the media type (compost or noncompost) averaged across 5–2–4 fertilizer treatments, and of the interaction between each fertilizer × media type. Contrasts within compost media were used to compare M201 and VCFL to SCOE and M201 to VCFL and to evaluate the interaction of these media effects with the effects of 5–2–4 fertilizer. M201 and VCFL were combined because their chemical characteristics are more similar than those of SCOE (Table 2). When interactions were significant at $P < 0.05$, the effect of fertilizer within the media type was evaluated using preplanned contrasts and Fisher's least significant difference. Effects were considered significant when $P < 0.05$. Statistical results of contrasts are provided in Supplemental Tables 1 to 11. At PS1, PMPO with 3–2–3 was inadvertently omitted from the experiment; therefore, preplanned contrasts to evaluate liquid fertilizer effects were valid only for VCFL. At PS2, SUN1 without 5–2–4 was accidentally omitted from block 1, and SCOE with 5–2–4 was accidentally omitted from block 2. To account for this, the analysis relied on least square means and adjusted least significant difference values for comparisons with treatments represented in only three blocks. For EC, pH, and plant tissue analyses, separate ANOVAs were used for each measurement date. Analyses were performed using the fit model standard least squares platform of JMP Pro software (version 15 or 16). The EC and growth measurements were log-transformed and counts were square root-transformed when needed to improve equality of variances.

Results and discussion

Growing media EC. Interpretation of EC measurements depends on the crop, production system, and plant growth stage. This discussion relied on guidelines developed with systems that use synthetic fertilizer to produce plugs, bedding plants, and potted plants for sale (Warncke 2015). Precise conversions are not available for EC methods used in this study, but values published for EC measured using the PT method provide an approximation (Cavins et al. 2000). Interpretations included the following: EC <0.75 (SME) or 1.0 (PT), very low, not enough nutrients for rapid growth; EC = 0.76 to 2.0 dS·m^{-1} (SME) or 1.0 to 2.6 dS·m^{-1} (PT), low, acceptable, or suitable for seedlings; EC = 2.0 to 3.5 dS·m^{-1} (SME) or 2.6 to 4.6 dS·m^{-1} (PT), optimum or normal for established plants; EC >3.5 (SME) or 4.6 (PT), high and may reduce growth; EC >5 (SME) or 6.5 (PT), very high, likely to reduce growth, and may lead to salt injury (Cavins et al. 2000; Warncke 2015).

The initial EC of M201 and that of VCFL were high enough to limit growth, both SCOE and SUN1 had an EC acceptable for seedling growth, and PMPO did not have enough nutrients for growth (Table 2). Additionally, M201 and VCFL had high levels of sodium, which would have contributed to the EC without providing any nutritional benefit. As expected, EC increased with fertilization (Table 3, Supplemental Table 1). Incorporating 5–2–4 fertilizer resulted in EC levels at 11 DAS that could reduce growth, even in media without high initial EC (PP1). A single top-dressing of 5–2–4 at the half rate frequently raised EC to potentially harmful levels in media with high initial EC (M201 and VCFL at PP2 and PS2). In media with a very low initial EC (PMPO), top-dressing at the half-rate led to EC suitable for seedlings; in media with low initial EC (SCOE and SUN1), top-dressing led to EC suitable for seedlings or established plants at 9 to 12 DAS. Early application of 3–2–3 fertilizer (PP1) brought media with very low initial EC (PMPO) into the normal range for established plants by 11 DAS. In media with high initial EC (VCFL), the early application of 3–2–3 fertilizer led to very high EC likely to reduce growth.

The increase in EC caused by fertilizer remained significant through measurements performed at 28 to 36 DAS (Table 3, Supplemental Table 1). With 5–2–4 fertilizer either incorporated or top-dressed, media generally had EC in the range suitable for seedlings, but it was low for established plants. With 3–2–3 fertilizer applied late in production (PP2 and PS2), media EC was in the normal range for established plants. With 3–2–3 applied beginning early in production (PP1), EC in PMPO was in the range suitable for seedlings; in VCFL, it was in the range for established plants. Without fertilizer, EC of noncompost media and that of the compost media SCOE were typically too low for growth, and both EC of M201 and that of VCFL were in the range suitable for seedlings. The results indicated that whether media contain compost or not and whether additional fertilizer is added or not, maintaining EC at levels appropriate for growth through the end of tomato transplant production is unlikely without frequent

Table 3. Electrical conductivity (EC; dS·m^{-1}) of five growing media with and without supplemental fertilizer 9 to 12 and 28 to 36 d after seeding (DAS) in three trials[i].

	9 to 12 DAS			28 to 36 DAS		
Treatment[ii]	PP1[iii]	PP2	PS2	PP1	PP2	PS2
M201	7.57 B[iv]	5.50 A	4.35 BCD	2.49 ABCD	1.62 BC	1.97 B
M201 + 5–2–4	10.55 A	5.59 A	4.72 ABC	3.36 A	1.94 B	2.05 B
PMPO	1.28 G	0.90 E	1.48 G	1.11 FGH	0.79 EFG	0.82 E
PMPO + 5–2–4	4.90 C	1.93 D	2.27 F	1.82 BCDEF	1.14 CDE	1.53 BC
SCOE	2.26 E	2.01 CD	3.75 DE	0.77 H	0.63 G	0.88 DE
SCOE + 5–2–4	5.20 C	3.02 B	4.03 CD	1.40 DEFG	1.15 CD	1.22 CD
SUN1	1.64 F	0.93 E	2.14 F	0.87 GH	0.73 FG	0.90 DE
SUN1 + 5–2–4	4.96 C	2.00 CD	3.17 E	1.42 CDEFG	1.30 CD	1.98 B
VCFL	6.02 BC	2.34 C	4.96 ABC	1.28 EFGH	0.94 DEF	1.60 BC
VCFL + 5–2–4	6.76 B	3.06 B	5.49 A	2.51 ABC	1.42 BC	1.42 C
PMPO + 3–2–3	3.42 D	0.97 E	1.53 G	2.16 ABCDE	4.09 A	3.66 A
VCFL + 3–2–3	7.12 B	2.28 CD	5.15 AB	3.14 AB	3.05 A	2.96 A
RMSE[v]	0.0731	0.0549	0.0602	0.1750	0.1113	0.0955

[i] Analysis based on log-transformed data; back-transformed means of three replications (or two for SUN1 and SCOE + 5–2–4 at PS2) are presented. 1 dS·m^{-1} = 1 mmho/cm.

[ii] M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not contain compost.

[iii] Trials conducted in Wanatah, IN, USA (PP1 and PP2) and West Lafayette, IN, USA (PS2). Measurements were taken at 11 and 36, 9 and 28, and 12 and 33 DAS at PP1, PP2, and PS2, respectively. EC was determined using a modified pour-through method (Wright 1986).

[iv] Means followed by the same letters do not differ significantly at $P < 0.05$ according to Fisher's protected least significant difference.

[v] RMSE = root mean square error for log-transformed data.

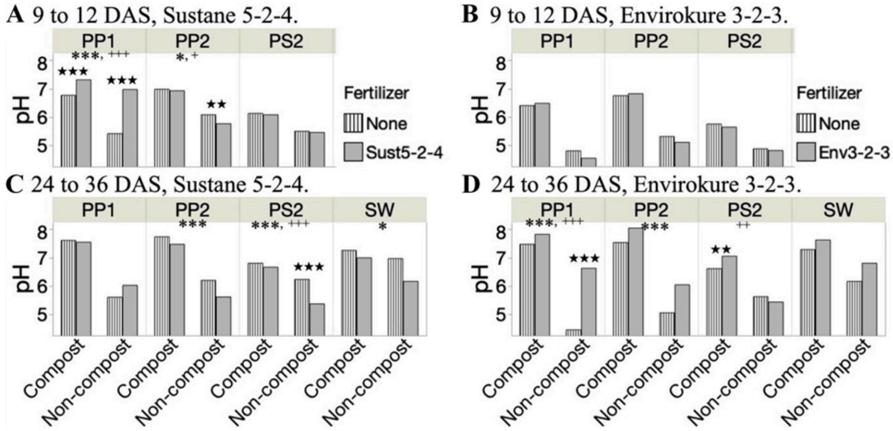

Fig. 1. Effect of fertilizer on pH of compost and noncompost growing media 9 to 12 (A, B) and 24 to 36 (C, D) d after seeding tomatoes (DAS) in trials at Wanatah (PP1, PP2), West Lafayette (PS2), and Vincennes (SW), IN, USA. (A, C) Sustane 5–2–4 fertilizer (Sust5–2–4). (B, D) Envirokure 3–2–3 fertilizer (Env3–2–3). *, **, * Statistically significant at $P < 0.001$, 0.01, and 0.05, respectively, for the main effect of fertilizer. $^{+++}$, $^{++}$, $^{+}$ Significant at $P < 0.001$, 0.01, 0.05, respectively, for interaction between fertilizer × media type (compost vs. noncompost). If the interaction was significant, then the significance of fertilizer within media type was as follows: ***, **, * $P < 0.001$, 0.01, and 0.05, respectively.**

applications of readily available nutrients.

Previous studies have documented similar results with solid organic fertilizers. Li and Mattson (2019) performed a study of cucumbers grown in peat/perlite medium and reported a rapid increase in growing media EC followed by a decline when N derived from composted turkey litter, feather meal, and bone meal was incorporated at 0.57 $kg \cdot m^{-3}$ (0.96 $lb/yard^3$). In that study, a vermicompost-based fertilizer applied at the same N rate also increased EC compared with the unfertilized media, but to a lesser extent. Without fertilizer additions, media EC can decrease by 50% within 10 d with regular overhead watering (Taylor et al. 2016).

Growing media pH. Initial media pH was within the recommended range (5.0–6.8) (A and L Great Lakes Laboratories, 2002) for M201, SUN1, and VCFL, low for PMPO, and high for SCOE (Table 2). The 5–2–4 fertilizer increased media pH measured 9 to 12 DAS only when it was incorporated into media (PP1) (Fig. 1A, Supplemental Table 2). By the end of the production cycle (24–36 DAS), the use of 5–2–4 before or after seeding reduced media pH by averages of 0.48, 0.39, and 0.43 points at SW, PP2, and PS2, respectively, but it did not affect pH at PP1 (Fig. 1C). At both times, changes in pH were larger in noncompost media and not always significant in compost media. The reduction in pH brought all media except PMPO closer to, but not always within, the desired range (Table 4); PMPO started with a low pH and, in some cases, 5–2–4 reduced the final pH below the desired range. A transient pH increase followed by a decrease to below the pH of unfertilized media after incorporation of a similar product were also reported by Li and Mattson (2019).

Liquid 3–2–3 applied before the early pH measurement did not change media pH measured 3 d later (PP1) (Fig. 1B, Supplemental Table 2). By the end of production, 3–2–3 frequently increased pH, but the effect was not consistent (Fig. 1D). The largest increases occurred at PP1, with 2.17 points in PMPO, and the next largest occurred at PP2, with 0.75 points averaged across PMPO and VCFL. The final pH in PMPO fertilized with 3–2–3 was within the desired ranged, but pH in VCFL was high (Table 4). The pH increase is, in part, explained by the alkalinity of the fertilizer solution: 425 ppm $CaCO_3$ equivalent when prepared using irrigation water with alkalinity of 155 ppm $CaCO_3$ equivalent. Therefore, it would be advisable to use 3–2–3 in systems where pH is monitored and can be readily adjusted. When that is not possible, using it in media with a low initial pH, such as PMPO, may be preferable.

Media pH changes are influenced by many factors, including the initial pH, buffering capacity of the medium, alkalinity of irrigation water, nitrogen mineralization and nitrification, temperature and moisture, plant nutrient uptake, and microbial activity (Argo and Biernbaum 1997). Taylor et al. (2016) found that compost and peat at the same initial pH have a similar buffering capacity on a dry weight basis. The smaller changes observed in compost media in this trial are probably caused by higher bulk density of those media (data not shown): a flat filled with compost media would have greater weight of media and, therefore, more buffering capacity than a flat filled with peat media. In a number of cases in this work, media pH exceeded 6.8, which is the upper limit of the recommended range, regardless of whether fertilizer was added. This occurred less often at PS2, where irrigation water was acidified to reduce alkalinity. We did not identify widespread negative effects on plants caused by media pH, perhaps because of the relatively short production cycle.

Seedling emergence. Emergence curves differed among treatments (Fig. 2). Across all growing media, when solid fertilizer was mixed into growing media before seeding (PP1, PS1, and SW) the time to 50% emergence was delayed by 1 to 2 d, emergence was less uniform in two of the trials, and maximum emergence at SW was reduced (Fig. 3, Table 5, Supplemental Table 3). Solid or liquid fertilizer applied after emergence had begun (PP2 and PS2) rarely affected emergence parameters. Media containing compost significantly delayed the time to 50% emergence by approximately 1 d in four trials and reduced emergence uniformity in the two trials at PP compared with media without compost.

In some trials, the effect of incorporating solid fertilizer was larger in compost media than in noncompost media or differed among compost media (Fig. 3, Table 5, Supplemental Tables 3 and 4). At SW, in noncompost media, maximum emergence with and without incorporated 5–2–4 differed by less than 1% on average; however, in compost media, incorporating 5–2–4 reduced emergence by an average of 6.7%.

Table 4. pH of five growing media with and without supplemental fertilizer 9 to 12 and 25 to 36 d after seeding (DAS) in four trials.

	9 to 12 DAS			25 to 36 DAS			
Treatment[i]	PP1[ii]	PP2	PS2	PP1	SW	PP2	PS2
M201	6.31 FG[iii]	6.84 B	6.52 A	7.63 A	7.24 ABCD	7.74 ABC	6.88 AB
M201 + 5–2–4	6.62 EF	6.88 B	6.37 AB	7.55 A	7.55 ABC	7.66 ABC	6.65 BC
PMPO	4.79 H	5.30 D	4.86 F	4.44 E	6.15 EF	5.04 G	5.61 E
PMPO + 5–2–4	6.92 DE	5.01 E	5.00 F	5.23 D	6.03 F	4.45 H	4.62 F
SCOE	7.57 B	7.33 A	6.09 BC	7.70 A	7.22 ABCD	7.91 AB	6.89 AB
SCOE + 5–2–4	7.97 A	7.22 A	6.29 AB	7.56 A	6.52 DEF	7.53 BCD	6.87 AB
SUN1	6.02 G	6.84 B	6.11 BC	6.74 C	7.76 A	7.33 CD	6.83 AB
SUN1 + 5–2–4	7.00 CD	6.50 C	5.89 CD	6.79 BC	6.27 EF	6.75 E	6.09 D
VCFL	6.39 FG	6.74 BC	5.74 DE	7.46 AB	7.27 ABCD	7.52 BCD	6.60 BC
VCFL + 5–2–4	7.31 BC	6.65 BC	5.55 E	7.49 A	6.87 BCDE	7.19 DE	6.43 C
PMPO + 3–2–3	4.53 H	5.09 DE	4.80 F	6.61 C	6.79 CDEF	6.03 F	5.42 E
VCFL + 3–2–3	6.47 F	6.81 B	5.63 DE	7.81 A	7.61 AB	8.03 A	7.04 A
RMSE[iv]	0.2610	0.1971	0.2298	0.4310	0.5580	0.3195	0.2104

[i] M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not.

[ii] Trials conducted in Wanatah, IN, USA (PP1 and PP2), Vincennes, IN, USA (SW), and West Lafayette, IN, USA (PS2). Measurements taken 11 and 36, 25, 9 and 28, and 12 and 33 DAS at PP1, SW, PP2, and PS2, respectively. pH was determined using a modified pour-through method (Wright 1986) or, at SW only, an ion-sensitive field-effect transistor.

[iii] Means of three replications (or two for SUN1 and SCOE + 5–2–4 at PS2) followed by the same letters do not differ significantly at $P < 0.05$ according to Fisher's protected least significant difference.

[iv] RMSE = root mean square error.

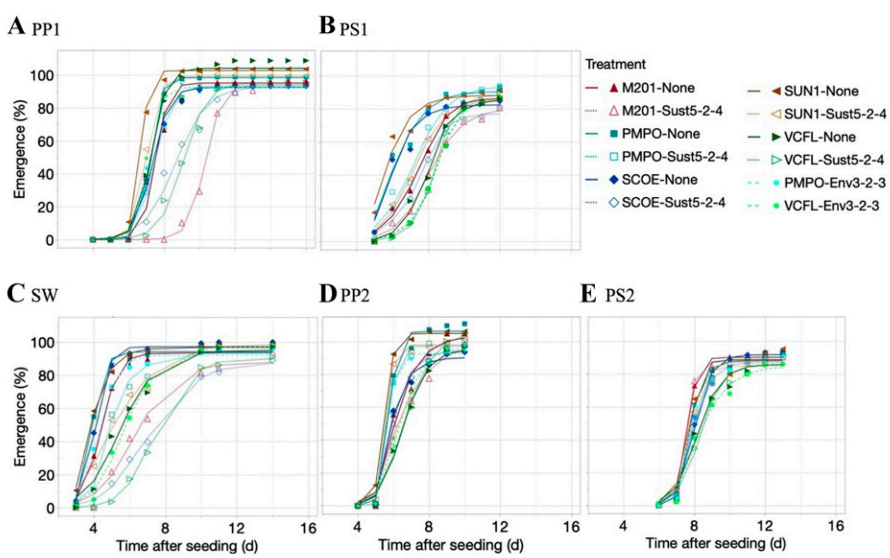

Fig. 2. Emergence vs. time after seeding for tomatoes grown in five growing media with and without supplemental fertilizer at Wanatah (A, D), West Lafayette (B, E) and Vincennes (C), IN, USA. Points are means of measured values. Lines connect means of values predicted by the equation $y = a/[1 + e^{-(x-b)/c}]$, where: y = % emergence and x = days after seeding. M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not contain compost. None, Sust5–2–4, and Env3–2–3 = without supplemental fertilizer, with 5–2–4, and with 3–2–3, respectively.

At PP1, for noncompost media, incorporating 5–2–4 delayed emergence by less than half a day; however, in compost containing media, the delays were approximately 1 d for SCOE, 1 to 2 d for VCFL, and 3 d for M201. At both PP1 and SW, incorporating 5–2–4 reduced emergence uniformity (increased parameter c) more in SCOE than in M201 and VCFL.

When the response to fertilizer did not depend on media type (i.e., when the fertilizer × media type interaction was not significant at $P < 0.05$), the main effects of media were of interest (Fig. 3, Supplemental Table 3). For the two noncompost media, emergence parameters did not usually differ. For compost media, emergence required one-half to 1 d longer in M201 and VCFL than in SCOE in two trials (PS1 and PP2) and was less uniform in M201 and VCFL than in SCOE in one trial (PP2). Emergence was faster in M201 than in VCFL in one trial (PS2), and it was more uniform in one trial (PS2) and less uniform in a second trial (PS1).

These results are consistent with those of our previous work that compared emergence in these media and illustrated the relationship between growing media EC and emergence parameters in which higher EC was associated with delayed and less uniform emergence (Maynard et al. 2024). In this trial, media EC measured 9 to 12 DAS was significantly higher when 5–2–4 was applied before seeding, and this was consistent with the delay in emergence and reduced uniformity and maximum emergence in some trials. Notably, negative effects of 5–2–4 occurred in all media, not only in the two compost media with high initial EC; however, the negative effects were often larger in compost media.

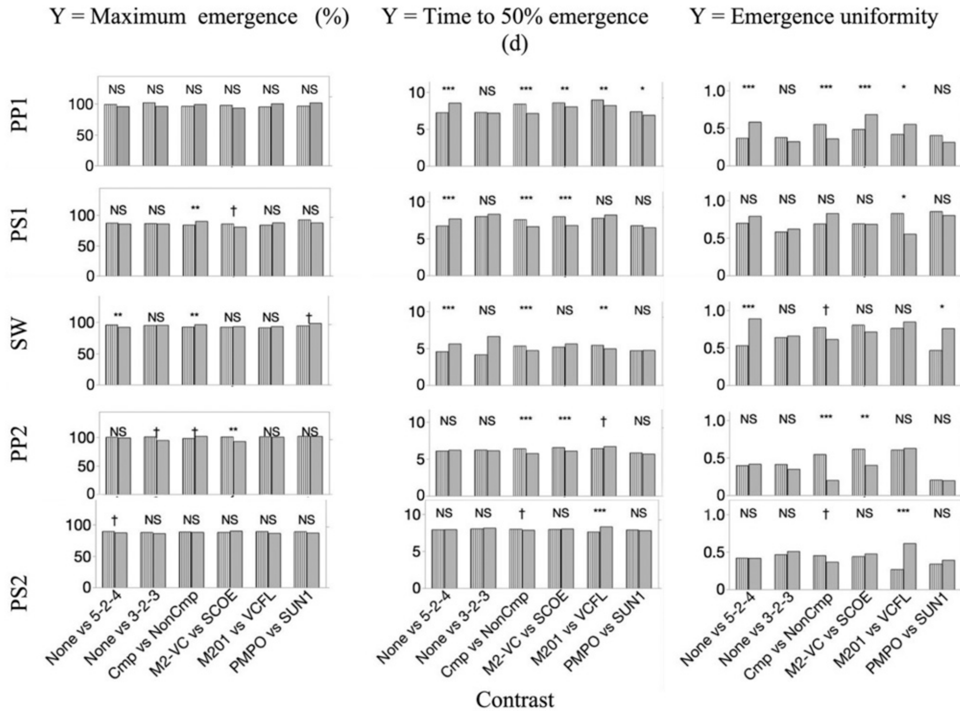

Fig. 3. Main effects of two fertilizers averaged across growing media and of media type averaged across fertilizers on estimated maximum emergence, days to 50% emergence, and uniformity of emergence for tomatoes grown at Wanatah (PP1, PP2), West Lafayette (PS1, PS2), and Vincennes (SW), IN, USA. For each contrast (A vs. B), the bar on the left is the mean of A and the bar on the right is the mean of B. None = no fertilizer; 5–2–4 = Sustane 5–2–4; 3–2–3 = Envirokure 3–2–3; Cmp = compost media; NonComp = noncompost media; M2-VC = M201 (Premium Flower 201) plus VCFL (Fort Light); SCOE = Seed Catapult; PMPO = Promix MP Organik; SUN1 = Sunshine No. 1 Natural and Organic. NS, *, **, *, † Nonsignificant or significant at $P < 0.001$, 0.01, 0.05, and 0.10, respectively.**

Li and Mattson (2019) also reported seedling injury consistent with high EC when they incorporated a product containing 8N–1.8P–3.3K from the same manufacturer into noncompost organic growing media at rates of 2.37 to 7.12 $kg \cdot m^{-3}$ (4 to 12 $lb/yard^3$). In that trial, EC measured using the PT method increased from less than 2 $dS \cdot m^{-1}$ to greater than 4 $dS \cdot m^{-1}$ at 20 DAS with the high rate of fertilizer; cucumber seedling survival was

Table 5. Estimated maximum emergence (*a*, %), days to 50% emergence (*b*), and emergence uniformity (*c*) derived from emergence data for tomato grown in five growing media with and without supplemental fertilizer in five trials.

	PP1[ii]			PS1			SW			PP2			PS2		
Treatment[i]	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
M201	95	7.5	0.36	86	7.4	0.75	94	4.4	0.50	103	6.3	0.54	90	7.6	0.27
M201 + 5–2–4	94	10.3	0.47	80	6.1	0.58	88	6.4	1.02	98	6.5	0.66	87	7.5	0.25
PMPO	99	7.2	0.31	90	8.3	0.89	94	3.9	0.31	106	5.8	0.23	89	7.8	0.29
PMPO + 5–2–4	93	7.5	0.49	94	8.4	0.95	94	5.0	0.61	97	5.8	0.17	88	7.9	0.39
SCOE	92	7.3	0.47	82	6.2	0.61	97	4.1	0.36	90	6.0	0.38	92	8.0	0.47
SCOE + 5–2–4	93	8.7	0.88	77	5.7	0.52	88	7.2	1.06	94	6.1	0.41	87	7.9	0.47
SUN1	103	6.7	0.24	88	8.0	0.76	97	3.9	0.50	105	5.6	0.22	88	7.7	0.41
SUN1 + 5–2–4	100	7.0	0.38	86	7.4	0.72	99	5.3	1.00	98	5.7	0.16	85	7.8	0.36
VCFL	104	7.3	0.43	86	7.2	0.69	95	5.6	0.95	95	6.6	0.59	86	8.2	0.63
VCFL + 5–2–4	95	9.1	0.66	88	8.0	0.87	90	7.6	0.73	105	6.7	0.66	86	8.3	0.58
PMPO + 3–2–3	98	7.2	0.28	–[iii]	–	–	92	4.3	0.52	93	5.8	0.16	86	7.8	0.31
VCFL + 3–2–3	93	7.1	0.35	85	7.2	0.66	97	5.9	0.79	96	6.4	0.53	85	8.4	0.70
RMSE[iv]	7	0.4	0.12	6	0.6	0.26	4	0.7	0.25	7	0.3	0.17	4	0.2	0.15
LSD[v] 0.05	NS	0.6	0.17	9	0.8	0.37	6	1.0	0.36	10	0.4	0.25	6	0.3	0.22

[i] M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not.

[ii] Trials conducted in Wanatah, IN, USA (PP1 and PP2), West Lafayette, IN, USA (PS1 and PS2), and Vincennes, IN, USA (SW).

[iii] No data.

[iv] RMSE = root mean square error.

[v] LSD = Fisher's protected least significant difference, $P \leq 0.05$.

reduced and root rot was observed. The manufacturer has suggested that an 8N–0.9P–3.3K formulation with lower EC than that of the 5–2–4 formulation is preferred by organic growers, with a recommended incorporation rate of 3.6 to 8.9 kg·m^{-3} (6–15 lb/yard^3) (Holden C, personal communication, 10 Mar 2020). The results reported here support the use of a lower rate of 5–2–4 when incorporated to avoid negative effects on emergence, particularly in media with an initially higher EC.

Seedling growth. Growth of tomatoes differed among treatments. Results were generally similar for fresh and dry weights, height, stem diameter, and leaf counts; therefore, only dry weight data are presented (Fig. 4). The relative growth rate (*b1*), its change over time (*c1*), and the final dry weight are most helpful for understanding the plant response (Fig. 5, Supplemental Tables 5 and 6).

When 5–2–4 was incorporated into compost media before planting (trials PP1, PS1, and SW), the results were inconsistent. In most cases, tomatoes grew more slowly and produced seedlings with lower dry weight than that of those in unfertilized media (Fig. 5, Table 6, Supplemental Tables 5–7); however, sometimes they grew more quickly (e.g. in VCFL at PP1 and SCOE at SW) or there was no difference in overall growth rate caused by 5–2–4 (e.g., M201 at PP1 and SW). When 5–2–4 was top-dressed onto compost media (trials PP2 and PS2), tomatoes usually grew more quickly than those without fertilizer, had a smaller decrease in relative growth rate, and produced up to twice the dry weight; however, in some instances, there was no significant effect of 5–2–4 (Fig. 5, Table 6, Supplemental Tables 5–7). Among the compost media, significant effects of topdressing 5–2–4 were observed least often in SCOE. Fertilizing VCFL with 3–2–3 increased plant dry weight up to 75%, but the effect was not consistent when 3–2–3 was first applied early in production (Fig. 5, Table 6). These inconsistent effects of fertilizer in compost media could be attributable to confounding by negative fertilizer effects on emergence timing in the case of 5–2–4 and variation in the availability of nutrients contained in the media caused by temperature, moisture, and leaching fraction variations among the trials.

In noncompost media, either incorporating or top-dressing 5–2–4 significantly increased the overall relative growth rate, reduced the decline in relative growth rate, and resulted in tomato seedlings with final dry weight 1.8- to 5.3-times greater than that of those without 5–2–4 (Fig. 5, Table 6, Supplemental Table 5). In contrast to compost media, any negative effects of 5–2–4 fertilizer on emergence that may have reduced growth were counteracted by the positive response to nutrients. Growth improved significantly more in SUN1 than in PMPO for at least one response in all trials except PS1 (Table 6, Supplemental Tables 5–7). SUN1 fertilized with 5–2–4 consistently produced plants as large as or larger than those grown in unfertilized compost media. In contrast, PMPO with 5–2–4 typically produced plants smaller than or the same size as plants grown in unfertilized compost media. It is possible that the low pH of PMPO observed during the initial media test and also at the end of production (Tables 2 and 4) limited mineralization of N in the fertilizer or limited plant nutrient uptake.

Fertilizing with 3–2–3 in PMPO increased the overall relative growth rate, reduced the decline in relative growth rate only when applied late in production, and increased final dry weight by 1.5- to 7-times (Fig. 5, Table 6, Supplemental Table 5). When 3–2–3 was first applied within 12 DAS (trials PP1 and SW), the effects were larger, and the final plant dry weight was the same as or greater than that of plants grown in compost media without fertilizer. When 3–2–3 was first applied later in the growing period (trials PP2 and PS2), plants were smaller than those grown in unfertilized compost media.

Treatments that consistently produced plants with the greatest final dry weight were VCFL + 3–2–3 applied at any time, VCFL + 5–2–4 top-dressed, PMPO + 3–2–3 applied early, and SUN1 + 5–2–4 incorporated.

Seedling nutrient concentrations. Both 5–2–4 and 3–2–3 significantly increased N and K concentrations (Fig. 6, Supplemental Table 8). According to Wilcox (1993), tomato seedlings are deficient in N or K if the aboveground concentration is less than 2.8% or 3%, respectively. Plants in both compost and noncompost media were often deficient in N by the end of the production cycle whether they received 5–2–4 fertilizer (Fig. 6A), usually deficient in K without 5–2–4, and deficient in K with 5–2–4 at PP2 (Fig. 6C). When the liquid 3–2–3 fertilizer was first applied early, the final tomato N concentration was insufficient, with an average of 1.85% (PP1), and the K concentration was below the adequate level (4%), but not deficient. When 3–2–3 was first applied several weeks after seeding, the final tomato N and K concentrations were sufficient, with average N values of 3.64% and 4.46%, and average K values of 4.50% and 5.61%, for PP2 and PS2, respectively. Earlier in production, at 24 DAS (PS2), all treatments had N and K concentrations above adequate levels, except for unfertilized noncompost media, which were deficient in both N and K, and unfertilized M201, which was deficient in N.

Fertilizer effects on tomato P concentrations at the end of production differed for 5–2–4 and 3–2–3 and differed for 5–2–4 incorporated into media or top-dressed, with increases in some cases and decreases in others (Fig. 6B, Supplemental Table 8). However, P concentrations were above the adequate level of 0.35% (Wilcox 1993) in nearly all cases. The two instances when P was deficient (<0.28%) occurred in noncompost media with fertilizer were as follows: PMPO with 3–2–3 at PP1 and SUN1 with 5–2–4 at PP2. A lower P tissue concentration with fertilization is probably explained by dilution of P in the plant tissue attributable to an increase in plant dry weight caused by the fertilizer.

The N and K deficiencies corresponded to final media EC less than 2.6 dS·m^{-1} in nearly all cases. When the N concentration was adequate (≥3.5%), final EC was always more than 2.6 dS·m^{-1}; however, in several cases, when the K concentration was adequate (≥4.0%), final EC was less than 2.6 dS·m^{-1}. This supports the suggestion (Cavins et al. 2000) that EC levels less than 2.6 dS·m^{-1} measured using PT indicate nutrient levels that are inadequate for established plants and emphasizes the unsuitability of the EC

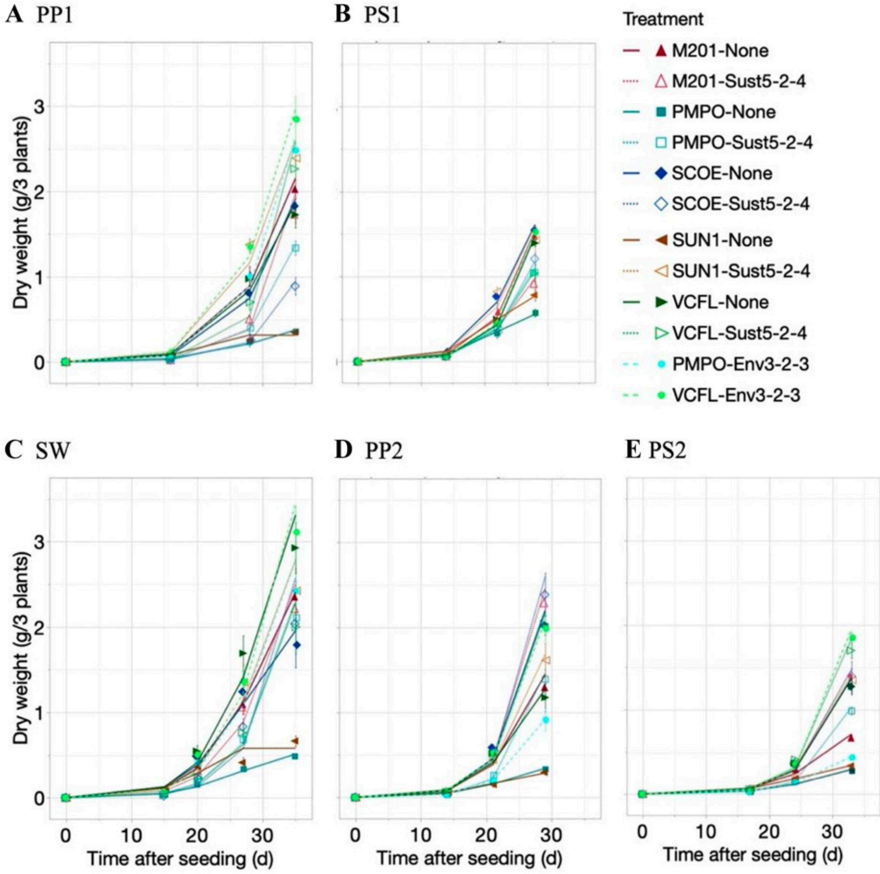

Fig. 4. Aboveground dry weight vs. time after seeding for tomatoes grown in five growing media with and without supplemental fertilizer at Wanatah (A, D), West Lafayette (B, E), and Vincennes (C), IN, USA. Error bars represent ± standard error of treatment means, and lines connect values predicted by natural log (y) = $a1 + b1x + c1x^2$. M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not contain compost. None, Sust5–2–4, and Env3–2–3 = without supplemental fertilizer, with 5–2–4, and with 3–2–3, respectively. 1 g = 0.0353 oz.

measurement alone for determining which nutrients are needed.

These results confirm previous findings that plants grown in these media are likely to be deficient in N after 4 to 5 weeks of growth without additional fertilizer (Maynard et al. 2024), similar to the results of studies of organic transplant production, as reviewed by Pascual et al. (2018) and Burnett et al. (2016). Plants are also likely to be deficient or close to deficient in K at that time. In noncompost media, this deficiency was more extreme and likely occurs much earlier than that in compost media. Results from PS2 show that deficiency can develop rapidly in the final weeks of the production cycle between 24 and 33 DAS. Tissue P concentrations are likely to be adequate regardless of whether supplemental fertilizer is applied.

The use of fertilizers following the protocols in this trial will improve tissue N and K concentrations at the end of the transplant production period, but these protocols are not optimized. The N concentration will likely be insufficient unless 3–2–3 fertilizer is applied frequently toward the end of production. The K concentration is likely to be higher than the 3.0% reported as deficient by Wilcox (1993) and fall within the range (2.6%–4.5%) reported for other trials in which potassium fertilization was intended to be adequate (Hartz et al. 2002; Lee et al. 2017; Widders and Garton 1992). When 3–2–3 is applied frequently toward the end of production, tissue K concentration may increase well above adequate levels. Creating media with lower initial K levels and/or using fertilizers with lower K may still provide adequate K while reducing the likelihood of harmful EC levels in media.

The tissue tests indicate that the N component of fertilizers was most important for improving plant growth, and that K was second most important. The fact that N was deficient by the end of the production cycle emphasizes the importance of understanding N release from organic media and fertilizers and N losses from growing media to effectively manage nutrient supply for seedlings. In this experiment, the total N applied in fertilizer treatments was calculated as sufficient to supply all N required by seedlings; however, clearly, adequate amounts were not available to plants in all fertilizer treatments, even in compost media that contained additional organic N.

Field performance. Size differences between unfertilized and fertilized transplants existed 4 weeks after transplanting (WAT) (Fig. 7, Supplemental Table 9). In noncompost media, both fertilizers significantly increased tomato plant dry weight (PS1 and PP2) and height (SW); increases ranged from 36% to 75% for dry weight and from 57% to 84% for height. In compost media, increases in size with fertilizer were smaller (average of 9%–19% for dry weight and 6%–18% in height) and not always significant. Stem diameter and leaf number showed similar trends (data not shown).

The ranking of plant size 4 WAT generally corresponds to the ranking in size at the end of transplant production, but there is one notable exception. At PP2, plants grown in PMPO with 3–2–3 first applied 3 weeks after seeding (WAS) had dry weight 4 WAT larger than that of plants from unfertilized PMPO or SUN1 and equivalent to that of all other treatments (Fig. 7C), even though these plants were smaller than any except unfertilized PMPO or SUN1 at the end of transplant production (Table 6). The rapid growth after transplanting required for this result seems likely related to the relatively high tissue N concentration at the end of seedling production when 3–2–3 was applied 3 WAS (PP2) (Fig. 6A). Research of conventional tomato production has documented the value of applying higher rates of fertilizer soon before transplanting to increase levels of readily available N in the seedling that

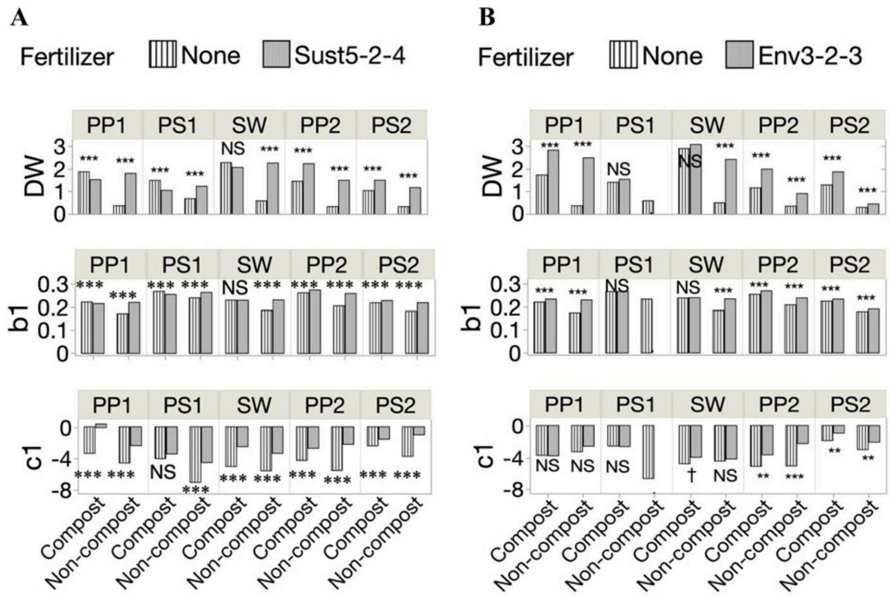

Fig. 5. Final dry weight (DW; g/3 plants) and growth parameters *b1* (relative growth rate) and *c1* (change in relative growth rate) for tomato seedlings grown with or without fertilizer in compost or noncompost media at Wanatah (PP1, PP2), West Lafayette, IN, USA (PS1, PS2), and Vincennes, IN, USA (SW). (A) Fertilized with Sustane 5–2–4. (B) Fertilized with Envirokure 3–2–3. NS, *, **, *, † Nonsignificant or significant at $P \leq 0.001$, 0.01, 0.05, and 0.10, respectively, for the effect of fertilizer within compost or noncompost media. 1 g = 0.0353 oz.**

can be used for vegetative growth during transplant establishment (Garton and Widders 1990; Widders and Garton 1992).

Fertilizers applied during seedling production influenced the early yield and fruit number produced by tomatoes at SW (Table 7). In noncompost media, 5–2–4 led to more than 4.5-times and 6.7-times the early weight and number, respectively, produced without 5–2–4, and 3–2–3 led to 9.4- and 16.5-times the early weight and number, respectively, compared with the unfertilized treatment (Table 7, Supplemental Tables 10 and 11). In compost media, neither 5–2–4 nor 3–2–3 significantly increased the early weight of fruit; however, in M201 only, 5–2–4 nearly doubled the early number. It is worth nothing that the coefficient of variation was high (40%); therefore, practically significant differences were not statistically significant.

Fertilizer effects on total production were more variable. In one compost media, M201, 5–2–4 significantly reduced total yield by 28%, but the 15% and 9% yield reductions in VCFL with 5–2–4 and 3–2–3, respectively, and the 7% yield increase in SCOE with 5–2–4 were not statistically significant (Table 7). Neither fertilizer significantly influenced total fruit number in compost media. In noncompost media (PMPO and SUN1), 5–2–4 did not significantly influence total yield, but it increased total fruit number by 29% (Table 7, Supplemental Table 11). In PMPO, 3–2–3 increased total yield by 30% and fruit number by 49% (Table 7). Across all media, average fruit weight decreased significantly by 12% to 13% with the use of either 5–2–4 or 3–2–3 fertilizer. In this trial, total yield was evaluated after 1 month of harvest. It is possible that if harvest had been extended beyond 1 month, then the results for total yield would have differed from those reported here.

At PP2 and PS1, the effect on yield was not measured directly, but the effects on number and stage of reproductive structures 4 WAT provide

Table 6. Final seedling dry weight for tomato grown in five growing media with and without supplemental fertilizer in five trials.

Treatment[i]	PP1[ii]	PS1	SW	PP2	PS2
	Dry wt (g/3 plants)[iii]				
M201	2.02 CD[iv]	1.47 AB	2.33 ABC	1.27 CD	0.66 D
M201 + 5–2–4	1.72 D	0.89 DE	2.21 BCD	2.28 A	1.39 B
PMPO	0.35 G	0.57 F	0.48 F	0.33 F	0.28 G
PMPO + 5–2–4	1.33 E	1.04 CD	2.10 CD	1.38 CD	0.98 C
SCOE	1.83 D	1.55 A	1.72 D	2.01 AB	1.26 B
SCOE + 5–2–4	0.87 F	1.20 BC	2.03 CD	2.34 A	1.37 B
SUN1	0.35 G	0.77 E	0.66 E	0.29 F	0.34 F
SUN1 + 5–2–4	2.38 ABC	1.40 AB	2.39 ABC	1.57 BC	1.35 B
VCFL	1.71 D	1.39 AB	2.88 AB	1.14 D	1.27 B
VCFL + 5–2–4	2.26 BC	1.02 CD	1.91 CD	2.03 AB	1.69 A
PMPO + 3–2–3	2.47 AB	No data	2.40 ABC	0.89 E	0.43 E
VCFL + 3–2–3	2.81 A	1.52 A	3.06 A	1.97 AB	1.85 A
RMSE[v]	0.129	0.153	0.1997	0.177	0.116

[i] M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not.
[ii] Trials conducted in Wanatah, IN, USA (PP1 and PP2), Vincennes, IN, USA (SW), and West Lafayette, IN, USA (PS2).
[iii] Dry weights were transformed before analysis using the natural logarithm to stabilize variances; means presented are back-transformed. 1 g = 0.0353 oz.
[iv] Means followed by the same letters do not differ significantly at $P < 0.05$ according to Fisher's protected least significant difference.
[v] Root mean square error (RMSE) is not back-transformed.

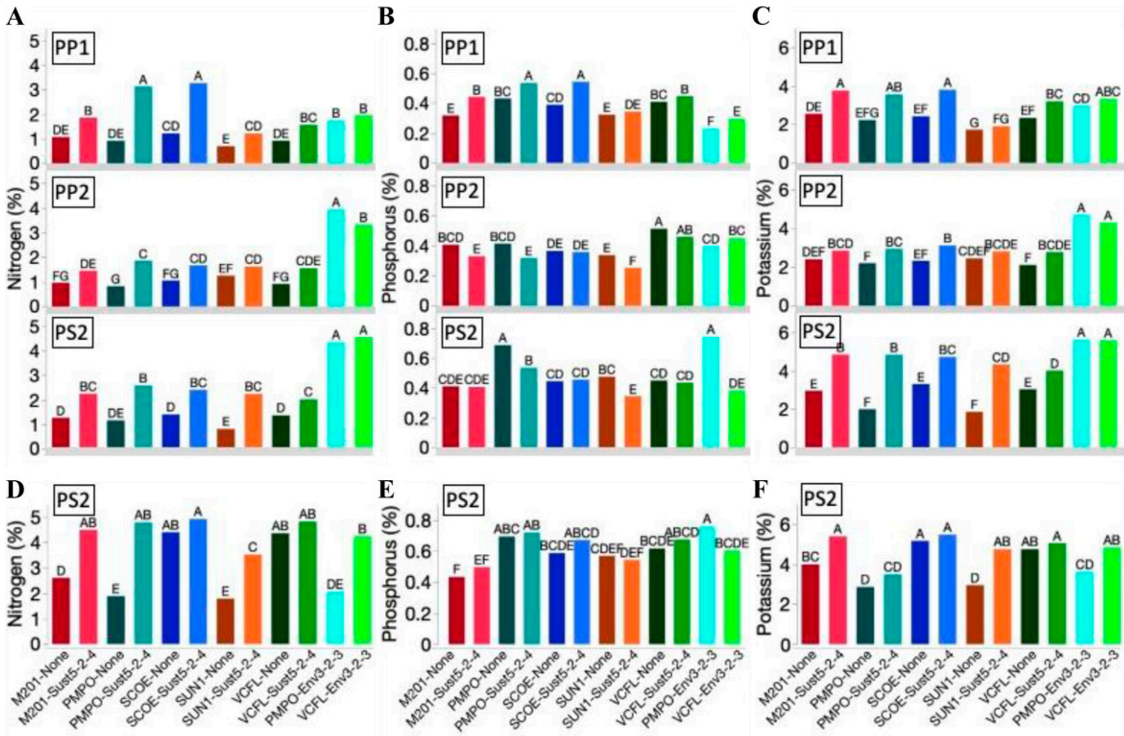

Fig. 6. Nitrogen (A, D), phosphorus (B, E), and potassium (C, F) concentrations of tomato seedlings grown in five growing media with and without supplemental fertilizer in Wanatah, IN, USA (PP1 and PP2) and West Lafayette, IN, USA (PS2). Samples were collected at the end of transplant growth 29 to 33 d after seeding (DAS) (A, B, C); at PS2, they were also collected at 24 DAS (D, E, F). M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not contain compost. None, Sust5–2–4, and Env3–2–3 = without supplemental fertilizer, with 5–2–4, and with 3–2–3, respectively. At PP1, 5–2–4 was mixed into growing media before seeding, and liquid 3–2–3 fertilizer was first applied as seedlings emerged and then periodically during growth. At PP2 and PS2, 5–2–4 was top-dressed twice at 7 or 10 DAS and 21 or 26 DAS, respectively, and 3–2–3 liquid fertilizer was applied beginning 22 or 26 DAS seeding and then daily four to five times. Bars within a graph labeled with the same letters do not differ significantly at $P < 0.05$ according to Fisher's protected least significant difference.

information on potential yield effects (Table 7, Supplemental Tables 10 and 11). The results show that, if any effect is observed, then the fertilizer use increases the number of fruit set on the first cluster and the number of clusters with open blooms or developing fruit by 4 WAT, and the effect is largest in noncompost media. This supports the finding at SW of increased early yield and fruit number in fertilized noncompost media.

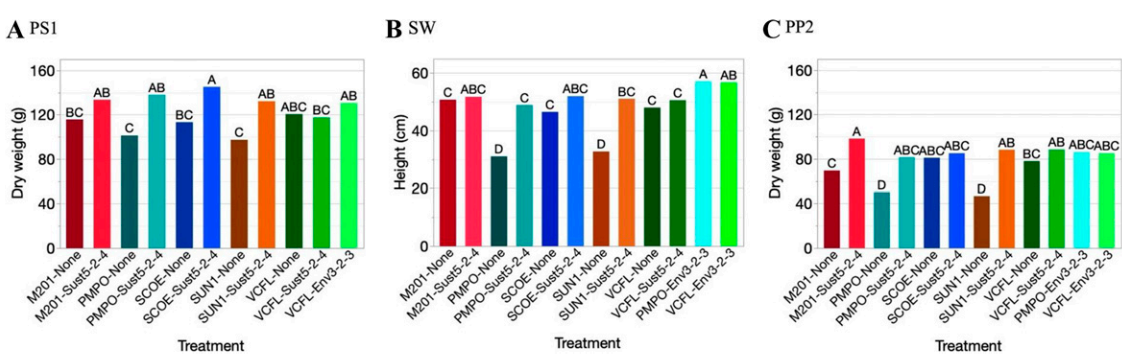

Fig. 7. Tomato plant size 4 weeks after transplanting seedlings that were grown in five growing media with and without supplemental fertilizer in three trials in Indiana. (A) Aboveground dry weight, trial PS1, West Lafayette, IN, USA. (B) Height, trial SW, Vincennes, IN, USA. (C) Aboveground dry weight, trial PP2, Wanatah, IN, USA. M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not contain compost. None, Sust5–2–4, and Env3–2–3 = without supplemental fertilizer, with 5–2–4, and with 3–2–3, respectively. Bars within a graph underwritten by the same letter do not differ significantly at $P < 0.05$ based on Fisher's protected least significant difference (1 g = 0.0353 oz; 1 cm = 0.3937 inch).

Table 7. Fruit set on first main stem cluster, flower clusters with open or past-bloom flowers, and yield for tomato grown as seedlings in five growing media with and without supplemental fertilizer.

Treatment[i]	Fruit set on first mainstem flower cluster (no./plant)		Flower clusters (PP2[ii])	Yield (SW) (kg/plot)[iii]		Fruit number (SW) (per plot)		Avg fruit wt (SW) (g)[iv]
	PS1	PP2[v]	(no./plant)	Early [vi]	Total[vi]	Early	Total	
M201	2.00	1.56 B[vii]	3.33 B	3.6 A	18.2 A	13.5 CD	67.8 AB	268 A
M201 + 5–2–4	2.58	3.56 A	5.67 A	4.8 A	13.1 CD	26.0 A	60.3 ABC	217 CDE
PMPO	2.08	0.08 C	1.33 C	0.6 B	12.9 CD	1.5 E	48.3 DE	266 A
PMPO + 5–2–4	2.25	2.38 AB	4.33 AB	4.1 A	14.6 BCD	20.0 ABC	63.5 ABC	229 CD
SCOE	1.58	2.34 AB	4.25 AB	3.7 A	14.3 BCD	15.8 BC	54.0 CDE	265 AB
SCOE + 5–2–4	2.08	2.8 AB	4.75 AB	4.0 A	15.3 ABC	18.8 ABC	63.0 ABC	242 ABC
SUN1	1.79	0.08 C	1.42 C	1.2 B	12.7 CD	4.3 DE	47.3 E	269 A
SUN1 + 5–2–4	2.25	3.33 A	5.00 AB	4.0 A	14.4 BCD	18.5 ABC	59.8 BCD	242 ABC
VCFL	2.38	1.55 B	4.00 AB	4.2 A	13.8 BCD	22.8 ABC	62.8 ABC	222 CDE
VCFL + 5–2–4	2.58	3.33 A	5.33 A	3.8 A	11.6 D	20.8 ABC	54.3 CDE	210 DE
PMPO + 3–2–3	–[viii]	3.57 A	5.08 A	5.6 A	16.8 AB	24.8 AB	71.8 A	234 BCD
VCFL + 3–2–3	2.21	3.33 A	4.5 AB	4.6 A	12.8 CD	26.8 A	67.0 AB	190 E
RMSE[ix]	0.52	0.3007	1.168	1.474	2.322	7.088	7.995	21.863

[i] M201 = Premium Flower 201; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. M201, SCOE, and VCFL contain compost; PMPO and SUN1 do not contain compost.

[ii] Trials conducted in Wanatah, IN, USA (PP2), Vincennes, IN, USA (SW), and West Lafayette, IN, USA (PS1).

[iii] 1 kg = 2.20 lb.

[iv] 1 g = 0.0353 oz.

[v] Analysis was performed on square root (fruit set) for PP2 to stabilize variance. Back-transformed means are presented. The RMSE is not back-transformed.

[vi] Early yield was harvested 8 through 15 Jul 2019, and total yield was harvested 8 Jul through 5 Aug 2019.

[vii] Means within a column followed by no letter or by the same letter do not differ significantly at $P < 0.05$ according to Fisher's protected least significant difference.

[viii] No data.

[ix] RMSE = root mean square error.

These yield outcomes are consistent with the work of Vavrina et al. (1998), who described the effects of increasing N application during transplant production on timing and quantity of tomato yield in conventional production. Of three studies of fresh market cultivars, two reported increased early yield and no effect on total yield with higher N application, and one reported increases in both early and total yields (Masson et al. 1991; Melton and Dufault, 1991; Weston and Zandstra 1989; all cited in Vavrina et al. 1998).

Differences between compost and noncompost media were clear in this trial, but differences among compost media are also important. Initial EC of SCOE was lower than that for VCFL and M201, in part as a result of lower nitrate-N, K, Ca, Mg, and Na (Table 2). This finding is likely the reason why incorporated 5–2–4 did not negatively affect emergence, growth, and yield in SCOE to the extent it did in M201 and VCFL. Unlike M201 and VCFL, SCOE contains sand, which could dilute compost salts and alter porosity and water-holding characteristics. In future work, it would be helpful to include a wider variety of compost media to identify categories that respond similarly to management practices.

The results clarified that nutrient limitation is likely in organic tomato transplant production in flats whether compost or noncompost media are used, and it might not be overcome even with application of fertilizer containing enough total N for plant needs. Of the fertilization practices used in this trial, the liquid 3–2–3 applied late resulted in sufficient tissue N and K concentrations at the end of the production period more reliably than treatments with incorporated or top-dressed 5–2–4 or earlier application of 3–2–3. That treatment also consistently led to final media EC measurements above the level suggested for established plants. This is probably because most of the N in 3–2–3 was in a readily available form, and fertilizer was applied more frequently and closer to the time of tissue and media sampling, likely reducing the percentage lost to leaching.

The experiment was not designed to identify optimal materials, rates, or timing of fertilizer application, but it illustrates the importance of tailoring these to initial media characteristics and provides information about the magnitude of effects that can be expected. If more specific information is not available, then categorizing media based on whether they contain compost provides a basis for differential guidelines. For example, in noncompost media, fertilizer is needed soon after emergence to support growth. Although incorporating additional fertilizer before seeding poses some risk to emergence in noncompost media, it still increases growth and yield. To avoid harming emergence, it is better to delay fertilizer application until after emergence. If liquid fertilizer is used in noncompost media, then early application will produce larger transplants than delaying application for 3 weeks, but plants that receive later application may perform as well in the field. This result should be confirmed, but it suggests that timing of liquid fertilizer application to noncompost media could be used to manage organic transplant size without detriment to field performance.

In contrast, in compost media, additional nutrients are probably beneficial, but they may not be essential to increase early or total yield. Incorporating additional fertilizer in compost media before seeding is not advised because it will likely inhibit emergence and possibly growth. Top-dressing or applying liquid fertilizer after emergence eliminates that risk, but caution is necessary because it could cause EC to exceed desirable levels early in production. Because compost media will likely provide adequate nutrients until the rapid increase in size that begins approximately 21 DAS, early application of nutrients is not critical. Delaying liquid nutrient application until that time will likely support growth at least as well as earlier fertilization and also improve tissue nutrient status at the end of transplant production.

Conclusions

With or without supplemental fertilizer, tomato seedlings grown in transplant trays in commercial organic media, with overhead irrigation, are likely to be N-deficient 4 to 5 WAS unless fertilizer with readily available N is applied 3 to 4 WAS. Supplemental fertilizer greatly improves growth and early yield of tomato seedlings in media that do not contain compost or significant other nutrient sources because of increased tissue N and K concentrations. If appropriately fertilized, then plants grown in noncompost media can perform as well as plants grown in compost media. In compost media, fertilizer does not have a consistent effect on seedling growth or early or total yield, although it does improve seedling nutrient status and lead to larger plants in the field. At the rates used in this study, incorporation of dry fertilizer before seeding can inhibit emergence, especially in compost media with high initial EC. Top-dressing dry fertilizer or applying liquid fertilizer 1 week or more after seeding and after emergence can prevent negative effects on emergence and growth.

The current product labels of organic fertilizers and growing media provide insufficient information for determining the appropriate rate or timing of fertilizer application for specific media. As is widely recognized, the ability to predict the timing and quantity of available N from fertilizers and organic components of media would be very helpful, but it will require significant focused research. Information that may be more readily available and would be useful include the salt index of the fertilizer and its expected effect on growing media EC, the pH and alkalinity of liquid fertilizer solutions at concentrations likely to be used, and the typical EC, pH, and soluble nutrient contents of commercial growing media products. This information would help producers when they select among the many media available for certified organic production and plan nutrient management for transplant production.

In addition, future work to develop and validate inexpensive tests that assess the need for fertilization during organic transplant production will help producers more effectively manage nutrients. Media EC is useful as a first step; however, because it does not distinguish among salts, it may not provide enough information for the wide variety of media and fertilizers used in organic production. Tests developed in concert with trials that include a variety of fertilizer types, rates, application methods and timings, growing media, and production conditions could lead to much more specific guidelines for producers. As the understanding of microbial roles in growing media and seedling nutrient acquisition deepens, these biological factors should also be investigated to inform management.

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