Tomato Seedling Performance in Commercial Organic Growing Media

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Abstract. Healthy transplants are critical to productivity in the field. For certified organic production in the United States, seedlings must be grown in media that meet the standards of the US Department of Agriculture's National Organic Program. Many commercial organic media options are available, they vary substantially in composition, and it is unknown to what extent this influences seedling performance. This project compared tomato (*Solanum lycopersicum* L.) seedling emergence and growth in seven commercially available media for organic production and evaluated posttransplant performance. Tomato seedlings were grown in greenhouses at Wanatah, West Lafayette, and Vincennes, IN, USA. Chemical characteristics of the media measured in saturated media extract ranged as follows: pH 5.2–7.5; electrical conductivity (EC) 0.79–4.68 dS·m^{-1}; 1–332 ppm nitrate-nitrogen, 5–69 ppm phosphorus, 41–451 ppm potassium, 78–714 ppm calcium, and 25–121 ppm magnesium. Higher media EC was associated with slower and less uniform seedling emergence and reduced total emergence. Seedling aboveground dry weights were significantly greater in media that contained compost. Relative performance in media containing compost varied across trials. The aboveground dry weight of tomato seedlings 4 weeks after transplanting did not differ for seedlings started in the five compost-based media, and those plants were significantly larger than plants started in the two media without compost. Larger plants tended to flower and set fruit earlier. Media testing protocols that predict nutrient supply over the production cycle could likely improve management in organic transplant production.

Vegetable seedlings should grow uniformly, reach the desired size and growth stage at the time of transplanting, and be free of disease and insect pests. The growing medium plays a critical role in producing healthy seedlings. A desirable medium provides water storage and adequate aeration to promote fast, uniform seed germination and subsequent strong root and top growth. In addition enough nutrients to support growth are essential unless they are added during production. Growing media also have the potential to introduce beneficial microorganisms that form close associations with seedlings and improve plant performance (Berg 2009; Gagné et al. 1993; Kokalis-Burrelle et al. 2002).

Sales of organic produce are growing rapidly in the United States. In the second quarter of 2020 sales exceeded $1.2 billion, representing a 17% to 18% year-over-year increase in sales and volume (Seeley et al. 2020). The number of farms in the United States certified to produce organic vegetables totaled 4075 in 2020. The number of operations using organic practices is likely much higher than the number of certified operations because farms selling direct to consumers are less likely to certify (Torres et al. 2017), and some small-scale farms are exempt from certification. Production of certified organic transplants for sale represents an additional side of the industry; 1043 farms are certified to produce transplants, including vegetables and flowers (US Department of Agriculture, Agricultural Marketing Service 2020).

For certified organic vegetable production in the United States, growing media must meet the standards of the US Department of Agriculture National Organic Program (NOP). These standards require that ingredients must be natural materials or synthetic ingredients that are on the National List of synthetic substances allowed for use in organic crop production, defined by the NOP (US Department of Agriculture, Agricultural Marketing Service 2023). No prohibited materials may be used, including synthetic starter fertilizers and wetting agents. There are many commercially available media in this category—the database maintained by the Organic Materials Review Institute (2023) includes more than 410 products. Ingredients frequently include one or more of peat, compost, coconut coir, vermiculite, and perlite. Animal, plant, and mined materials are often incorporated by the manufacturer to provide additional nutrients and adjust pH. The diverse ingredients and their combinations create media with very different chemical and physical characteristics; information on these features is often not available from product descriptions, but they are likely to have a profound effect on vegetable seedling performance (Cantliffe 2009).

Meeting the nutrient needs of seedlings is likely to be one of the most significant challenges when using organic growing media (Cantliffe 2009). A survey of Maine organic growers of ornamental bedding plants validated this assessment: more than half reported that managing substrate, pH, and fertility represented a major production challenge (Burnett and Stack 2009). Several review papers summarized knowledge about growing media accepted for use in organic production. Burnett et al. (2016) reviewed both substrates and fertilizers for container production in greenhouses in the United States, Pascual et al. (2018) considered substrates for organic transplant production in Europe, and Bergstrand (2022) focused on organic fertilizers in European greenhouse production systems.

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All three discussed the challenges of supplying nutrients in organic transplant production. The unpredictability of nutrient release from organic nutrient sources incorporated into or applied during production is a key issue. Bergstrand (2022) emphasized the need for better control of the nutrient supply—both the total quantity and the timing of nutrient availability to plants. For vegetable transplants, the small volume of growing media used in many production systems increases the challenge of providing nutrients.

Both Pascual et al. (2018) and Burnett et al. (2016) focus on compost as a substitute for a portion of the peat in growing media. Many organic growing media contain compost. Compost can provide nutrients; influence water-holding capacity, porosity, and drainage; alter the pH; and raise EC, all of which affect seedling growth. The main drawbacks of compost cited in the reviews are high EC, pH above 7, and low water-holding capacity. Burnett et al. (2016) also noted that the variability of composts due to regional differences in inputs and production methods means that substrates containing compost may require close management by growers.

Pascual et al. (2018) reported that growing media containing 25% to 50% compost by volume typically permit better plant growth than media with more or less compost. Burnett et al. (2016) indicated that growers making their own growing media use compost at 20% to 50%. Pascual et al. (2018) assumed that media containing compost at 40% by volume will supply adequate amounts of nutrients for transplant production for 2 to 3 weeks, except for nitrogen (N). Burnett et al. (2016) concluded that organic fertilizer incorporated into growing media should supply nutrients for 4 to 5 weeks. All three review papers noted that the amount of N available to plants is difficult to predict because it will depend on temperature, moisture, and substrate characteristics, including carbon to N ratio, stability of organic matter, and microbial activity.

In summary, the peer-reviewed literature indicates that vegetable transplant production in growing media approved for organic production may require application of nutrients during the production cycle for best results. However, there is not a well-documented means of determining whether a particular organic growing medium contains enough nutrients for a particular crop cycle, or how long a nutrient supply will last under various conditions. This makes it more difficult for growers to create an integrated plan for transplant production that includes informed selection of growing media, nutrient management, and production schedules.

This project was initiated to compare tomato (*Solanum lycopersicum* L.) seedling growth in seven commercially available media for organic production, and evaluate media effects on emergence, seedling growth, and posttransplant performance. No fertilizers were added during production so that seedling growth would depend on nutrients supplied by the media. The objective is to improve farmers' knowledge about commercial organic media and understand how it influences transplant production.

Materials and methods

Growing media. Seven growing media approved for organic production were used in the trials: Johnny's 512 Mix (J512), Premium Flower 201 (M201), Penn Valley Potting Soil (PENN), Promix MP Organik (PMPO), Seed Catapult (SCOE), Sunshine No. 1 Natural and Organic (SUN1), and Fort Light (VCFL) (Table 1). The media were selected to include products manufactured in nearby states, products manufactured farther away but used in the region, and products with and without compost. Uses recommended by manufacturers include seed starting (PMPO), seed starting and growing on (J512, PENN, SCOE, SUN1, VCFL), and transplanting flowers and houseplants into containers (M201). Major ingredients and manufacturers are provided in Table 1. Square pots (4.0 inches wide and 3.6 inches high with a volume of 39.4 $inch^3$; HC Companies, Twinsburg, OH, USA) were filled with samples of media, placed on a greenhouse bench, watered to saturation (determined by water just starting to drip from holes in pots), maintained moist for 3 d by watering as needed, and then transferred to plastic bags and sent to a commercial laboratory (A & L Great Lakes Laboratories, Fort Wayne, IN, USA) for saturated media extract analysis (SME) (Warncke 1998). Wetting media before analysis allows amendments incorporated into the media during production, such as lime, to undergo initial reactions that would not occur in dry media.

Emergence and seedling performance. Five similar greenhouse trials were conducted in 2018 at three Indiana locations described in Table 2, two each at Pinney Purdue Agricultural Center (PP) and Horticulture and Landscape Architecture Plant Growth Facility (PS), and one at Southwest Purdue Agricultural Center (SW). The establishment of trials in different types of structures with varying degrees of climate control, watering schedules and amounts based on local technician judgment, and on different planting dates represented diversity that can be found on farms producing organic transplants.

The seeding dates at PP corresponded to dates for early and middle transplant dates for field tomatoes. At PS, two trials were seeded and ran concurrently, representing a schedule for a late-transplanted field crop. The seeding date at SW corresponded to a typical date for field-planted tomatoes.

Each trial was set up as a randomized complete block design with four replications and seven treatments representing the growing media listed in Table 1. In each trial the experimental unit was a 72-cell plug tray with square cells 1.52 inches across and 2.25 inches deep with a volume of 3.60 $inch^3$ (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 but were not otherwise used for data collection. Details of greenhouse environmental conditions and seeding dates are provided in Table 2.

In each trial, flats were filled with media, seeded with 'Big Beef' tomato (Johnny's Selected Seeds, Winslow, ME, USA), and then watered until water leached from holes in the bottom of the cells. In some trials it was observed that some media was not fully saturated even though the water was dripping out the bottom, and so media was further irrigated with repeated overhead watering and/or by temporarily placing the flat in a tray of water.

Moisture retained in the media was determined by weight. Five unfilled flats

Table 1. Manufacturers and major ingredients of growing media used in trials comparing growth of tomato seedlings.

Name	Code	Manufacturer	Major ingredients[i]
Johnny's 512 Mix	J512	Johnny's Selected Seeds, Winslow, ME, USA	Peat (brown and black), compost (poultry manure, hardwood shavings/sawdust, crop residue, and/or seaweed), perlite, fish meal, seaweed meal
Premium Flower 201	M201	Morgan Composting, Sears, MI, USA	Peat, compost (dairy manure), worm castings, TN brown rock
Penn Valley Potting Soil	PENN	Penn Valley Farms, Lititz, PA, USA	Peat, coir, compost (poultry manure), perlite, biochar, pulverized volcanic ash, chelated trace minerals, limestone
Promix MP Organik	PMPO	Premier Tech Horticulture, Quakertown, PA, USA	Peat, coir, perlite, vermiculite, limestone, mycorrhizae –GHA297
Seed Catapult	SCOE	Ohio Earth Food, Hartville, OH, USA	Peat, compost (layer manure), perlite, vermiculite, sharp sand, humate, rock phosphate, azomite, mycorrhizal fungi
Sunshine No. 1 Natural and Organic	SUN1	Sun Gro Horticulture, Agawam, MA, USA	Peat, perlite, limestone, organic starter nutrient charge, gypsum, silicon, organic wetting agent
Fort Light	VCFL	Vermont Compost, Montpelier, VT, USA	Peat (blonde), coir, compost (manure, bark, plant materials), perlite, vermiculite, herbs, granite, basalt, blood meal, bone meal, kelp meal, gypsum

[i] Information provided by manufacturer.

were weighed to determine the average weight of an empty flat. Flats were weighed after seeding before watering and again after the initial watering and drainage. At PP and PS, flats were also weighed periodically during seedling production.

Flats were watered as needed based on observation to maintain moderate moisture in the growing media. At SW, flats were placed on germination mats set to maintain 80 °F until 90% of seeds emerged. At other locations, flats were placed on greenhouse benches with no supplemental heat.

Emergence was recorded daily from when first observed until at least 90% of seedlings had emerged. Plant growth was measured three times during seedling production, first ~14 days after seeding (DAS) and then at 7- to 10-d intervals. At each measurement, three randomly selected plants were cut at the soil level. The leaf number on each plant was recorded. The combined fresh weight of the three plants was recorded, plants were then dried to constant weight in an oven set at 55 to 60 °C, and the dry weight was recorded. At the final growth measurement, plant

Table 2. Experimental locations in Indiana, USA, greenhouse covering and environment, and dates of seeding and transplanting for trials comparing growth of tomato seedlings in seven growing media approved for use in organic production in 2018.

Location characteristic	Pinney Purdue Agricultural Center (PP)	HLA Plant Growth Facility and Purdue Student Farm (PS)	Southwest Purdue Agricultural Center (SW)
City	Wanatah, IN, USA	West Lafayette, IN, USA	Vincennes, IN, USA
Latitude, longitude	41.4427754°N, 86.9312414°W	40.420540°N, 86.914152°W	38.739094°N, 87.487703°W
Greenhouse covering	Double poly	Polycarbonate	Double poly
Daily temp [mean ± *SD* (°F)][i]			
Trial 1	69.9 ± 4.8	75.9 ± 2.9	69.2 ± 6.1
Trial 2	78.2 ± 4.6		No trial 2
Daily light integral [mean ± *SD* ($mol \cdot m^{-2} \cdot d^{-1}$)]			
Trial 1	19.1 ± 10.2	21.7 ± 6.6	No data
Trial 2	25.6 ± 9.5		No trial 2
Seed date			
Trial 1	13 Mar	14 May	21 Mar
Trial 2	2 May	14 May	No trial 2
Transplant date	2 Jun	11 Jun	4 May
Soil type	Tracy sandy loam[ii]	Mahalasville-Treaty complex, silty clay loam[iii]	Alvin fine sandy loam[iv]
Soil organic matter (%)	2.2	4.8	1

[i] *SD* = standard deviation; (°F − 32) ÷ 1.8 = °C.
[ii] Mixed, active, mesic Ultic Hapludalf.
[iii] Mixed, superactive, mesic Typic Argiaquoll.
[iv] Mixed, superactive, mesic Typic Hapludalf.

height and diameter of the stem below the cotyledons were measured on the sampled plants. At SW, a fourth measurement was taken 44 DAS just before transplanting to the field because there was a delay between the final greenhouse measurement and transplanting due to field conditions.

The final plant samples from PP trials 1 and 2 were sent to a commercial laboratory (Brookside Laboratories, New Bremen, OH, USA) to determine nutrient concentration following methods described by Miller et al. (2013): method P2.02 for N and method P4.30 for minerals. Analysis from one site could provide the basis for understanding the results observed at that site. If plant growth results were similar at the other experimental sites, the analysis could suggest explanations for results at those sites also.

Field performance. At each location, tomatoes from one greenhouse trial at that location were transplanted into the field. Each field trial was arranged as a continuation of the associated greenhouse trial: a randomized complete block design with four replications and seven treatments. An experimental unit consisted of six plants. 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 18 inches apart in a single row on beds covered with 4-ft-wide black plastic mulch (PP: 1 mil embossed, Filmtech Corp, Allentown, PA, USA; SW: 0.8 mil, Ginegar Plastic, Inc., Santa Maria, CA, USA) or at PS with 6-ft-wide black woven weed mat (DeWitt Company, Sikeston, MO, USA). Beds were 10 ft on center at PP, 3 ft at PS, and 6 ft at SW. At PS and SW, plants were supported with a Florida weave trellis. At PP, plants were not supported. 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 12-inch emitter spacing, at SW 8-inch emitter spacing; 0.24 gal/h per emitter at 8 psi).

Plant survival was assessed ~1 week after transplanting (WAT). Vegetative growth was evaluated 12 and 26 d after transplanting (DAT) at PP; 14, 21, and 28 DAT at PS; and 12, 18, and 27 DAT at SW by counting the number of nodes with 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, the fresh and dry weights of three randomly selected plants from each plot were determined.

Reproductive stage was evaluated on the sample dates by recording the most advanced stage of development on the first main stem flower cluster of each plant: bud longer than 5 mm, open flowers, or fruit set. The number of plants at each stage was determined for six plants in each experimental unit at PP and SW and three plants in each experimental unit at PS. At PS the numbers of buds, open flowers, and fruit set on all clusters were also recorded on each sample date.

Data analysis. Maximum emergence, days to 50% emergence, and emergence uniformity were estimated for each experimental unit by fitting the sigmoid equation $y = a/[1 + e^{-(x - b)/c}]$, where: y = percent emergence, x = DAS, a = maximum emergence, b = days to 50% emergence, and c is related to how steep the sigmoid curve is; a smaller value indicates steeper curve and therefore more uniform emergence. The Nonlinear platform of JMP software (version 13.2.0; 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 equation $\ln(y) = a1 + b1\,X1 + c1\,X2$, where $X1$ and $X2$ are orthogonalized values of x (DAS) and x^2, and y is fresh weight or dry weight. To include aboveground weights of 0 on day 0, 0.01 and 0.001 were added to fresh and dry weight per three plants, respectively, to allow calculation of ln (y) before parameter estimation (Snedecor and Cochran 1980). Parameter $a1$ represents the intercept, parameter $b1$ the slope or overall relative growth rate, and parameter $c1$ the departure from a constant relative growth rate throughout the experiment, with negative values indicating a slowing of the relative growth rate. The Fit Model, Standard Least Squares platform of JMP software (version 13.2.0) was used to estimate parameters.

The first analyses of variance (ANOVA) were designed to determine whether the five trials could be combined in analysis to evaluate treatment (media) effects across all trials. The second ANOVAs were designed to determine whether the two trials within a location (PP or PS) could be combined in analysis. These ANOVAs included trial, treatment (media), and trial × treatment as fixed effects, and rep within trial as a random effect. Several emergence and seedling growth responses showed significant interaction ($P < 0.05$) between trial and treatment across all trials, between trial and treatment at PP, but not between trial and treatment at PS (data not shown). Therefore, the results presented here are based on ANOVAs for emergence and seedling growth data conducted separately for PP1, PP2, PS (trials 1 and 2 combined), and SW. Plant dry weight after transplanting did not show significant trial × treatment interaction and so analysis across the trials was performed. ANOVAs across trials included trial and treatment (media) as fixed effects and rep within trial and trial × treatment as random effects. ANOVAs within a trial included rep and treatment as fixed effects. Treatment means were separated with Fisher's protected least significant difference test at $P < 0.05$. Analyses were performed with JMP software (version 13 or 14) Fit Model Platform, Standard Least Squares, and for mixed models, REML options. Growth measurements were log-transformed when needed to improve equality of variances and normality of residuals (Wilson 2007).

The significance of trial and treatment effects on reproductive stage 4 WAT was evaluated by logistic regression using the Nominal Logistic platform of JMP Pro (version 16.1.0) with trial and treatment as fixed effects, reproductive stage (none, bud, open flower, or fruit set) as the categorical response, and counts summed across replications as the frequency. The lack of fit provided a test of trial × treatment interaction.

To evaluate the association between initial media EC and emergence parameters, treatment means across trials were regressed on media EC reported from the SME analysis. Regressions were performed using the

Fit Y by X platform of JMP software (version 14). A linear trend significant at $P < 0.05$ indicated that the independent variable could explain a significant proportion of variation in the dependent variable, with the proportion indicated by the value of r^2. Quadratic trends were not significant.

Results and discussion

Growing media. SME analyses for the growing media are presented in Table 3. pH ranged from 5.2 (PMPO) to 7.5 (PENN). EC ranged from 0.79 (SUN1) to 4.68 (VCFL) $dS \cdot m^{-1}$. Nitrate-nitrogen (NO_3-N) was less than 10 ppm in PENN, PMPO, SCOE, and SUN1, and more than 100 ppm in J512 and VCFL. Phosphorus (P) ranged from 4.8 (J512) to 68.6 (SCOE) ppm, and was higher than 10 ppm in all except J512. Potassium (K) ranged from 41 (SUN1) to 451 (VCFL) ppm and was more than 150 ppm in all except SUN1. Calcium was lowest in PMPO, 78 ppm, and highest in VCFL, 714 ppm. Magnesium was lowest in SCOE (25 ppm) and highest in VCFL (121 ppm). Iron ranged from 13.6 to 45.7 ppm, manganese from 4 to 29.5 ppm, sulfur from 48 to 532 ppm, and sodium from 28 to 194 ppm. Boron (<0.1 to 0.2 ppm), zinc (1.9 to 5.7 ppm), and copper (<0.1 to 0.6 ppm) exhibited smaller ranges.

Although the media used in this study cannot represent all commercial organic media in the market, these results indicate a wide variation in chemical and nutrient characteristics of organic media. In a survey of chemical and physical properties of 24 retail potting media, Wiberg et al. (2005) also found much variation.

Seedling emergence. Emergence curves differed among media in all trials (Fig. 1). Predicted maximum emergence (parameter *a*) showed the least difference among media: significant differences were detected in only one trial, PP2. In that trial SUN1, VCFL, and SCOE had greater predicted maximum emergence than PENN and M201, and J512 and PMPO were intermediate.

The speed of emergence as reflected in parameter *b*, estimated days to reach 50% emergence, was fastest for SUN1, SCOE, and PMPO in all trials, ranging from 4.3 to 4.8 d at PP2 and SW, 5.6 to 6.2 d at PS, and 7.3 to 7.8 d at PP1. The slowest emergence, ranging from 6.9 to 11.0 d to reach 50% emergence, occurred in VCFL and M201, with VCFL significantly slower than M201 in most trials (PP2, PS, and SW).

The uniformity of emergence, or the time period from beginning to end of emergence, is reflected in parameter *c*: smaller values mean more uniform emergence. SCOE, J512, SUN1, and PMPO did not differ significantly in any trial, had the most uniform emergence in all trials, and were always more uniform than VCFL.

Differences in emergence among media could be partly explained by media EC measured in the preplant SME test. Regression analysis indicated that EC of the growing media accounted for 79% of the variation in maximum emergence ($P = 0.007$), 87% of the variation in days to emergence ($P = 0.002$), and 66% of the variation in emergence uniformity ($P = 0.025$). Days to 50% emergence increased, and maximum emergence and emergence uniformity decreased with increasing EC.

The ECs of PENN, PMPO, SCOE, and SUN1 were within the acceptable range for young plants (0.5–2.0 $dS \cdot m^{-1}$) (A&L Great Lakes Laboratories 2002). SUN1 met the more stringent guidelines (0.4–1.0 $dS \cdot m^{-1}$) suggested for germinating seedlings in plugs by Styer and Koranski (1997). ECs of J512 and M201 were within the desired range for mature plants (0.7–3.5 $dS \cdot m^{-1}$), and the EC of VCFL was considered high (Warncke 2015).

The inhibitory effect of salinity on seed germination for a variety of species is well-documented (Ibrahim 2016), and the literature also includes specific examples of this in tomato (Singh et al. 2012). These results also confirm prior reports of high EC as a common problem in compost-containing growing media that can interfere with germination and reduce growth in some species (Rogers 2017).

It is likely that media moisture also contributed to differences in emergence. Differences among media in the speed of emergence were largest at PS (Fig. 1C). The volume of water retained in flats after seeding was lower at PS than at other sites: across media treatments, the weight of water per flat averaged 145 ± 51 g for PS1 and 166 ± 17 g for PS2, vs. 756 ± 22 g for PP1, 808 ± 31 g for PP2, and 784 ± 19 for SW. Although flats at all locations were watered after seeding until drainage was observed,

Table 3. pH, EC, nitrate-nitrogen, and plant mineral nutrients in aqueous extract of seven growing media before planting tomatoes in 2018.

Medium[i]	pH[ii]	EC[iii] ($dS \cdot m^{-1}$)[iv]	NO_3-N	P	K	Ca	Mg	B	Fe	Mn	Zn	Cu	Na	S
			(ppm)[v]											
J512	6.9	2.72	101	4.8	391	311	42	0.1	40.7	10.7	5.7	0.2	133	226
M201	6.0	2.97	28	12.6	285	580	101	0.2	43.3	19.2	4.1	0.4	134	532
PENN	7.5	1.50	3	31.2	219	202	45	0.1	19.3	10.8	2.8	0.6	53	107
PMPO	5.2	1.12	2	29.1	176	78	35	0.2	19.9	4.0	1.9	0.1	67	48
SCOE	6.4	1.43	1	68.6	160	119	25	<0.1	22.3	9.9	3.1	<0.1	56	62
SUN1	6.5	0.79	1	15.3	41	172	30	<0.1	13.6	3.9	1.7	0.3	28	48
VCFL	6.1	4.68	332	35.7	451	714	121	0.2	45.7	29.5	5.4	0.6	194	395

[i] J512 = Johnny's 512 Mix; M201 = Premium Flower 201; PENN = Penn Valley Potting Soil; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. See Table 1 for manufacturer and major ingredients of media.
[ii] pH measured in 1:2 v/v mix of medium and deionized water; others measured in saturated media extract with DTPA (diethylenetriamine penta-acetic acid) (Warncke 1998).
[iii] EC = electrical conductivity; NO_3-N = nitrate-nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; B = boron; Fe = iron; Mn = manganese; Zn = zinc; Cu = copper; Na = sodium; S = sulfur.
[iv] 1 $dS \cdot m^{-1}$ = 1 mmho/cm
[v] 1 ppm = 1 $mg \cdot kg^{-1}$

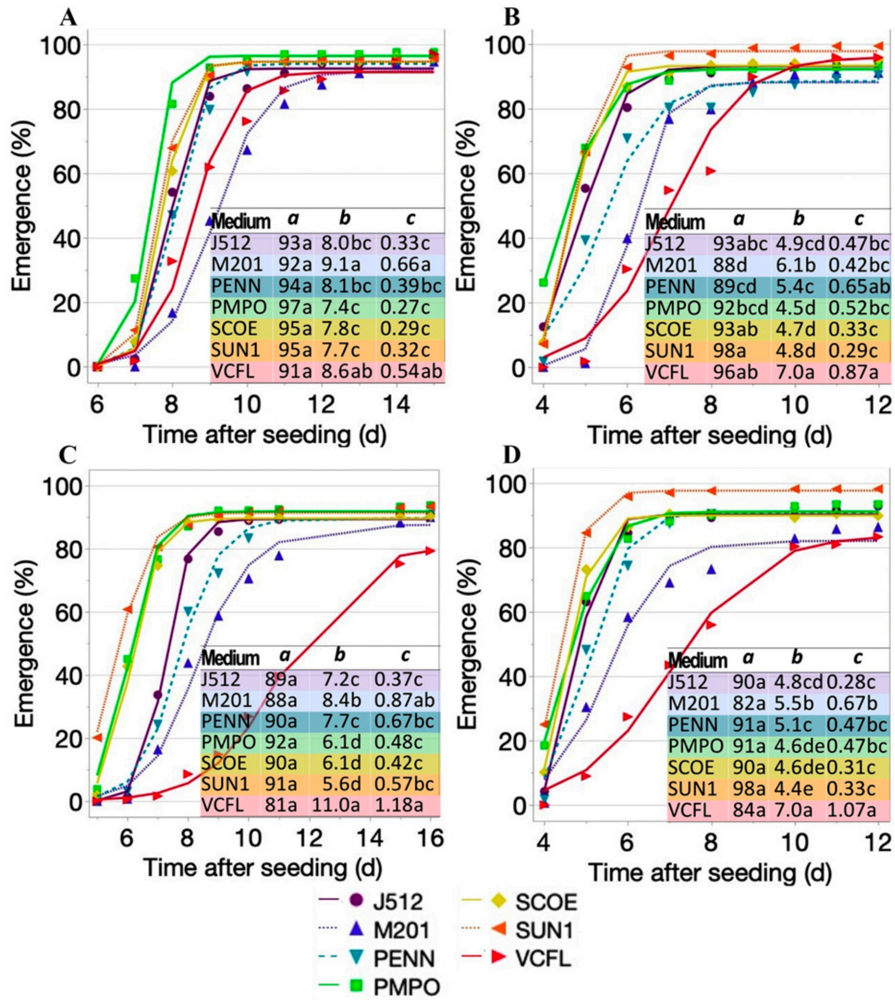

Fig. 1. Emergence of tomato grown in seven growing media in 2018 at Pinney Purdue Agricultural Center, Wanatah, IN, USA (A, B); Horticulture and Landscape Architecture Plant Growth Facility, West Lafayette, IN, USA (C); and Southwest Purdue Agricultural Center, Vincennes, IN, USA (D). Points are means of measured values. Lines connect means of values predicted by parameters *a* (maximum emergence), *b* (days to 50% emergence), and *c* (emergence uniformity) from the equation $y = a/[1 + e^{-(x - b)/c}]$, where: y = % emergence and x = days after seeding. Treatment means for parameters are shown in tables with graphs; means followed by the same letter within a column are not significantly different by a least significant difference test at $P = 0.05$. J512 = Johnny's 512 Mix; M201 = Premium Flower 201; PENN = Penn Valley Potting Soil; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. See Table 1 for manufacturer and major ingredients of media.

observations indicated that media at PS did not absorb water readily because it had dried out in the warm greenhouse between flat filling and seeding. Subsequent waterings at PS gradually increased the amount of water retained but it was not until 15 DAS that the amount of water retained in a flat came within 10% of the amount recorded just after seeding at PP and SW (data not shown). At PP, media with the slowest emergence, VCFL and M201, were noted to be more difficult to wet (data not shown). Wetting the media before filling flats probably would have reduced the difficulty in wetting media after seeding that occurred in some instances. Manufacturer guidelines explicitly recommend prewetting media in some cases (e.g., J512, PENN and VCFL).

Seedling growth. Growth of tomatoes differed among growing media. Results were generally similar for fresh and dry weight, stem diameter, height, and leaf counts, so only dry weight data are presented (Fig. 2). The final dry weight, the relative growth rate (parameter *b1*), and its change over time (parameter *c1*) are most helpful in understanding the plant response.

The final dry weight was largest for VCFL and SCOE at PP1; VCFL at PP2; SCOE, J512, and PENN at PS; and SCOE, PENN, J512, and VCFL at SW. Plants grown in M201 were consistently intermediate in dry weight at all locations. PMPO and SUN1 produced the smallest dry weight at all locations, with PMPO significantly smaller than SUN1. Over all trials, plants in SCOE, VCFL, J512, and PENN averaged 70% heavier than plants in M201, and 3.3 and 7.2 times heavier than plants in SUN1 and PMPO, respectively.

The relative growth rate was fastest at PP and SW for tomatoes grown in SCOE and VCFL, although not always significantly faster than for J512 or PENN. At PS, the relative growth rate was fastest for SCOE, J512, and

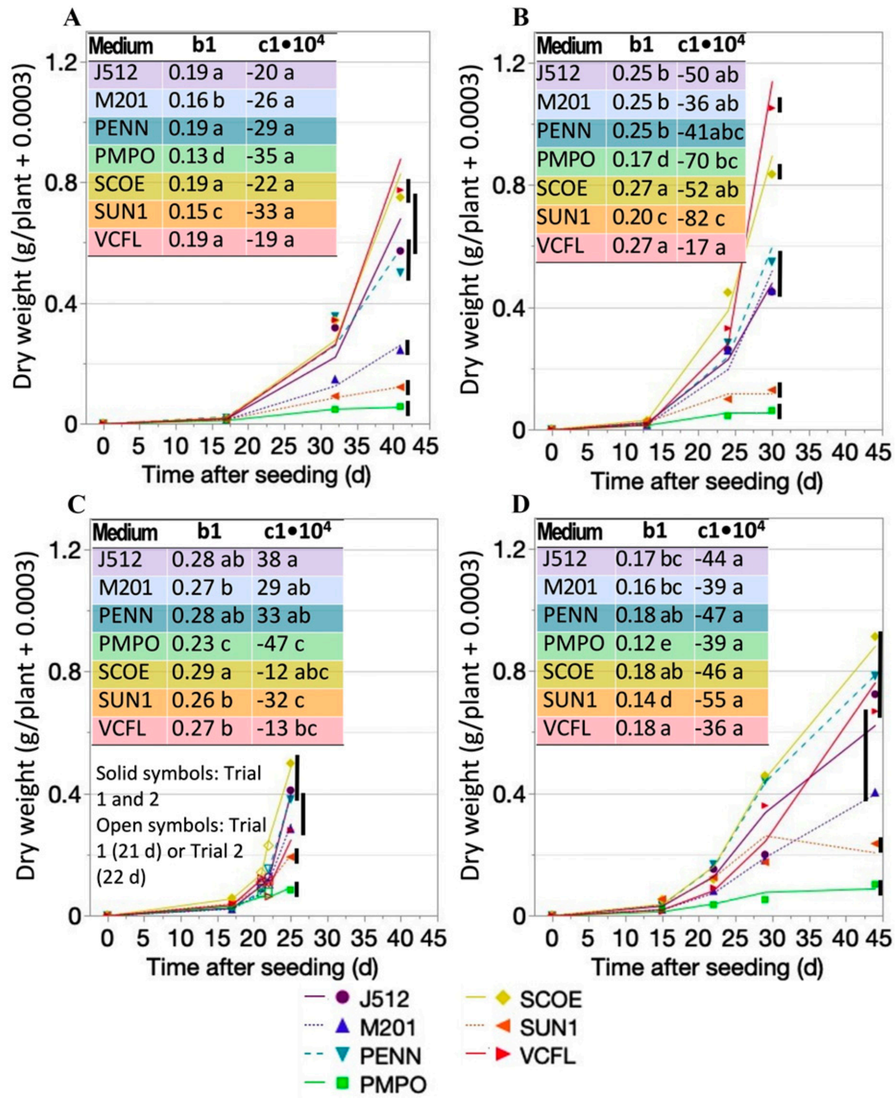

Fig. 2. Aboveground dry weight vs. days after seeding for tomatoes grown in seven growing media during the seedling stage at Pinney Purdue Agricultural Center, Wanatah, IN, USA (A, B); Horticulture and Landscape Architecture Plant Growth Facility, West Lafayette, IN, USA (C); and Southwest Purdue Agricultural Center, Vincennes, IN, USA (D), in 2018. Points are geometric means of measured values. Lines connect geometric means of values predicted by parameters *a1*, *b1*, and *c1* for the equation ln (y) = $a1 + b1\ X1 + c1\ X2$ where *X1* and *X2* are orthogonalized values of x (days after seeding) and x^2, and y is dry weight (g/plant + 0.00033). Treatment means for parameters *b1* and *c1* are shown in tables with graphs; means followed by the same letter within a column are not significantly different by a least significant difference test at $P = 0.05$. Final dry weight values connected by black vertical bars are not significantly different by a least significant difference test at $P = 0.05$. 1 g = 0.0353 oz. J512 = Johnny's 512 Mix; M201 = Premium Flower 201; PENN = Penn Valley Potting Soil; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. See Table 1 for manufacturer and major ingredients of media.

PENN. PMPO had the slowest relative growth rate at all locations, and SUN1 was only slightly better.

Tomato seedling relative growth rate slowed over time in all media at PP and SW, and for SCOE, VCFL, SUN1, and PMPO at PS, as indicated by negative values of *c1*. In general the relative growth rate slowed the most for PMPO and SUN1: the values of *c1* for these two media were significantly less than the highest value in all trials except for SW, where PMPO did not differ from the top value. The relative growth rate slowed the least in VCFL, J512, SCOE, and M201 at PP1; VCFL at PP2; J512, PENN, M201, and SCOE at PS; and VCFL, M201, PMPO, and J512 at SW.

Root growth was not measured in this experiment but it is likely that it was influenced by treatments. Decreases in both tomato root and shoot growth have been documented at EC of 5 dS·m^{-1} caused by nutrients or by sodium chloride (NaCl), with shoot weight showing a relatively greater decrease due to NaCl (Schwarz and Grosch 2003). Both nutrients and NaCl contributed to EC in media used in this experiment. Although preplant EC measured by SME did not reach 5 dS·m^{-1} (Table 3), the value of 4.68 for VCFL approaches 5 dS·m^{-1} and could reasonably be expected to have caused reductions in root and shoot growth compared with media with lower EC, nutrient, and NaCl concentrations. It is important to recognize that EC can change rapidly when media is leached with water (Cretu et al. 2011). In this research, media was regularly watered to the point of leaching after seedlings emerged, so it is expected that EC would have decreased over the course of the experiment, and reductions in root and shoot growth due to high EC would have diminished over time. As mentioned in the discussion of emergence results, at PS, media did not appear to receive enough water to fully wet and leach media at the start of the experiment, and so EC would have decreased more slowly at that location than at PP and SW. It is possible that at PP and SW, leaching reduced EC quickly enough so that it did not limit growth, while at PS, EC remained high enough to limit growth in addition to delaying emergence. This is consistent with PS being the only location where plants grown in VCFL were not among those with the highest overall growth rate or greatest dry weight (Fig. 2).

Across all trials, tomatoes generally grew better in the media that contained compost than in media that did not: they were typically larger, with faster relative growth rates that did not decrease as much over time.

In the case of vegetable transplants, the largest plants are not always the most desirable. As Dufault (1998) explains, commercial transplanting equipment may not be able to handle larger seedlings, and larger seedlings may lead to excessive stand loss due to transplant shock. In this study, the largest tomatoes were of reasonable size for transplanting by hand or with water wheel or carousel transplanters commonly used by producers in the United States.

Growing media that supports fast growth is desirable for transplants because it can reduce the time required for growing the seedlings, resulting in reduced costs for labor, heat, and other expenses associated with greenhouse use. A potential disadvantage of media that supports fast growth is that it may reduce the strategies available to the grower for managing the seedling growth. Growers typically manage growth rate and relative growth of shoot and roots by adjusting watering, temperature, and/or nutrient supply (Berghage 1998; Dufault 1998; Liptay et al. 1998). With a growing media that supports fast growth, it may not be possible to make adjustments by managing the nutrient supply, if high nutrient levels in the media are responsible for the high growth rate.

Seedling nutrient concentrations. Seedling tissue concentrations of N, P, and K differed significantly for tomatoes grown in different media (Table 4) in the two trials at PP. At the time of sampling, tomato leaves were chlorotic and plants appeared to be deficient in N, observations consistent with the relatively low concentration of N in plants from all media: less than 1.3%. Sufficiency levels for whole tomato seedling nutrient concentrations are not published, but N concentrations in these seedlings were lower than many reports in the literature for tomato seedlings that performed well in the field (Hartz et al. 2002; Vavrina et al. 1998; Widders and Garton 1992). In PP1, plants grown in VCFL and SCOE did not differ and had significantly higher N concentration than plants grown in any other media. In PP2, plants grown in VCFL had the highest N concentration, followed by SCOE, which did not differ from M201 and PMPO. In both trials, plants grown in SUN1 had the lowest N concentration, although not significantly different from several other media.

The media NO_3-N measured before seeding using the SME protocol (Table 3) did not correspond well to the plant tissue N concentration at the end of the study. Although tissue N concentrations were the highest in VCFL and SCOE, the NO_3-N level in SCOE was less than 40 ppm, putting it in the low category for soilless media (Warncke 2015), whereas the NO_3-N level in VCFL was more than 200 ppm, putting it in the high category. This lack of correspondence is not unexpected: the preplant measurement of NO_3-N would not necessarily reflect the total plant-available N in the media due to presence of other forms of N in the media (e.g., ammonium and organic compounds), mineralization rates of organic N, and differential leaching of NO_3-N during production (Bergstrand et al. 2019).

Tomato P concentration was significantly higher for plants grown in PMPO than any other media, 0.821% and 0.682% in PP1 and PP2, respectively. The lowest tissue P concentrations were in J512 (0.280%) and SUN1 (0.342%) in PP1, and in SUN1, SCOE, VCFL, and J512 in PP2 (0.339% to 0.400%). The high P concentration of plants grown in PMPO probably reflects concentration of P in plant tissue due to growth being limited by another factor; plants grown in PMPO were the smallest in the trial. The growth-limiting factors for PMPO were likely the combination of low N and low pH in the growing media (Table 3). As measured by the preplant SME test, J512 contained acceptable levels of P (3–5 ppm), M201 and SUN1 contained high levels (11–18 ppm), and the four other media contained very high levels of P (>19 ppm) (Warncke 2015).

Potassium concentration of tomato seedlings in PP1 was highest in

Table 4. Nitrogen, phosphorus, and potassium concentration of tomato seedlings grown in seven media at Wanatah, IN, USA, in 2018.

	Nitrogen		Phosphorus		Potassium	
	PP1[i]	PP2[i]	PP1	PP2	PP1	PP2
Medium[ii]	(%)					
J512	0.923 B[iii]	0.753 C	0.270 D	0.400 BCD	2.49 AB	2.26 A
M201	0.828 B	0.893 B	0.458 B	0.412 BC	2.16 C	2.57 A
PENN	0.843 B	0.768 C	0.491 B	0.451 B	2.36 BC	2.36 A
PMPO	0.798 B	0.883 B	0.821 A	0.682 A	2.18 C	2.42 A
SCOE	1.180 A	0.988 B	0.467 B	0.374 CD	2.46 AB	2.25 A
SUN1	0.768 B	0.730 C	0.342 CD	0.339 D	1.60 D	1.84 B
VCFL	1.170 A	1.207 A	0.414 BC	0.374 CD	2.60 A	2.57 A

[i] Tomatoes were grown for 42 and 30 d, respectively, in trials PP1 and PP2 in Wanatah, IN, USA, 2018.
[ii] J512 = Johnny's 512 Mix; M201 = Premium Flower 201; PENN = Penn Valley Potting Soil; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. See Table 1 for manufacturer and major ingredients of media.
[iii] Means followed by the same letter within a column are not significantly different by a least significant difference test at $P = 0.05$.

VCFL, 2.60%, followed by J512 and SCOE, which were not significantly lower. In PP2 tissue, K concentration in VCFL was 2.57% and did not differ from any other except SUN1. SUN1 had the lowest tissue K concentration in both trials (1.60% to 1.84%). This reflects the much lower level of soluble K in SUN1 media (41 ppm) compared with other media (Table 3). SUN1 was the only media with K level in the low range, 0 to 59 ppm (Warncke 2015). PENN, PMPO, and SCOE contained K in the optimum range (150–259 ppm), M201 contained K in the high range (250–349), and J512 and VCFL contained K in the very high range (>350 ppm) (Warncke 2015).

Media EC values are often used to provide a general indication of the level of available nutrients at a point in time. The tissue concentrations of N and K tended to increase as media EC measured before planting increased (Tables 3 and 4), but tissue concentrations of P did not. SCOE was an exception to the trend for N: although EC was the third lowest for SCOE, tissue N was the second highest. At the start of production, all media were above the minimum EC of 0.7 suggested for mature plants in conventional production systems where inorganic nutrients would be applied regularly (Warncke 2015). In this research, when no additional nutrients were added during production, none of the media had adequate levels of all nutrients to support seedlings throughout the production cycle. This highlights the need for additional research to clarify how EC relates to nutrient availability in organic media to account for differences in nutrient release (Bergstrand et al. 2019), partial salt index per unit of nutrient (Rader et al. 1943), and high levels of sodium in compost that contribute to EC without providing essential plant nutrients (e.g., Sánchez-Monedero et al. 2004).

The tissue tests from trials at PP suggest that N was a limiting factor for plant growth after emergence. This is consistent with findings of Russo (2005) and Nair et al. (2011) that tomato seedlings growing in organic media could benefit from nutrient applications containing N in addition to other nutrients. Melton and Dufault (1991) documented that shoot growth of tomato increases readily when N is added during the seedling stage. Plant growth results were generally similar at the other experimental sites, suggesting that N likely limited growth there also.

Field performance. Tomato seedlings from all media survived for 1 WAT except at SW, where survival of seedlings grown in PMPO averaged 88% (data not shown). Tomato plant fresh and dry weight in the field 4 WAT showed similar trends and so only dry weight is reported in Table 5. Plants started in VCFL had the largest dry weight, but were not significantly different from those in SCOE, PENN, M201, or J512. Plants started in SUN1 were smaller than these but significantly larger than plants started in PMPO, which were the smallest.

Plants were largest at PP. This may be in part because plants at PP were not supported in a trellis-weave system. Differences in soil fertility could also have played a role: the sandy soil at SW had the lowest percent organic matter of the three locations (Table 2) and had not been managed organically, so the soil supply of N would likely have been lower than at PP and PS.

The reproductive stage of plants 4 WAT was significantly affected by both trial and treatment [$P < 0.001$ (Fig. 3)]. No significant interaction between trial and treatment was found ($P = 0.281$). Plants grown in VCFL were the most likely to have fruit, followed by plants grown in SCOE, then PENN and J512, and then M201 (Fig. 3A). Plants grown in SUN1 and PMPO were the least likely to have flowered. This is consistent with the findings of Vavrina et al. (1998) that increasing N supply to spring-grown tomato transplants led to increased yield at first harvest: in this study, seedlings with the highest tissue N concentration (VCFL and SCOE) were most likely to flower within 4 WAT, and seedlings with the lowest tissue N concentration (SUN1 and PMPO) were the least likely to flower in that time period. The counts of buds, flowers, trusses, and fruit at PS showed a similar pattern in terms of relative earliness of plants started in different media (data not shown). The significant trial effect reflected the fact that plants at PS were more likely to have open flowers or fruit than plants at PP or SW (Fig. 3B), possibly because at PS seedlings were transplanted later in the season when warmer temperatures would have led to faster development.

Because field plots were not fertilized, it is possible that these results are not relevant to farm situations in which adding nutrients before transplanting or during crop production is common. However, it has been shown that fertilization and nutritional status of seedlings do influence earliness and yield of field-grown tomatoes when standard field fertilization practices are followed (Garton and Widders 1990; Vavrina et al. 1998). Results from this study indicate that nutrient supply in the growing media probably explains at least part of the differences in observed seedling growth. Therefore, it seems likely that if in this study fertilizer had been applied to the fields, differences in plant growth and flowering would still have been observed among the media treatments—although their magnitudes might have differed from the results observed without field fertilizer.

The rationale for not applying fertilizer in this study was 2-fold. Plants were grown in the field for only 4 weeks

Table 5. Tomato plant dry weight 4 weeks after transplanting for plants grown in seven growing media during transplant production at Wanatah, West Lafayette, and Vincennes, IN, USA in 2018.

Medium[i]	Dry wt (g/plant)[ii]
J512	52.3 A[iii]
M201	53.8 A
PENN	53.7 A
PMPO	32.4 C
SCOE	58.4 A
SUN1	42.2 B
VCFL	60.9 A
Trial[iv]	
PP2	75.1 A
PS2	56.3 B
SW	28.8 C

[i] J512 = Johnny's 512 Mix; M201 = Premium Flower 201; PENN = Penn Valley Potting Soil; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. See Table 1 for manufacturer and major ingredients of media.

[ii] Dry weights were transformed before analysis using the natural logarithm to stabilize variances; means presented in table are back-transformed. Medium values are means of four replications in each of three trials; trial values are means of 28 experimental units in each trial. 1 g = 0.0353 oz.

[iii] Medium or trial means followed by the same letter are not significantly different by a least significant difference test at $P = 0.05$.

[iv] PP2 = Pinney Purdue Agricultural Center (Wanatah, IN, USA), trial 2; PS2 = HLA Plant Growth Facility and Purdue Student Farm (West Lafayette, IN, USA), trial 2; SW = Southwest Purdue Agricultural Center (Vincennes, IN, USA).

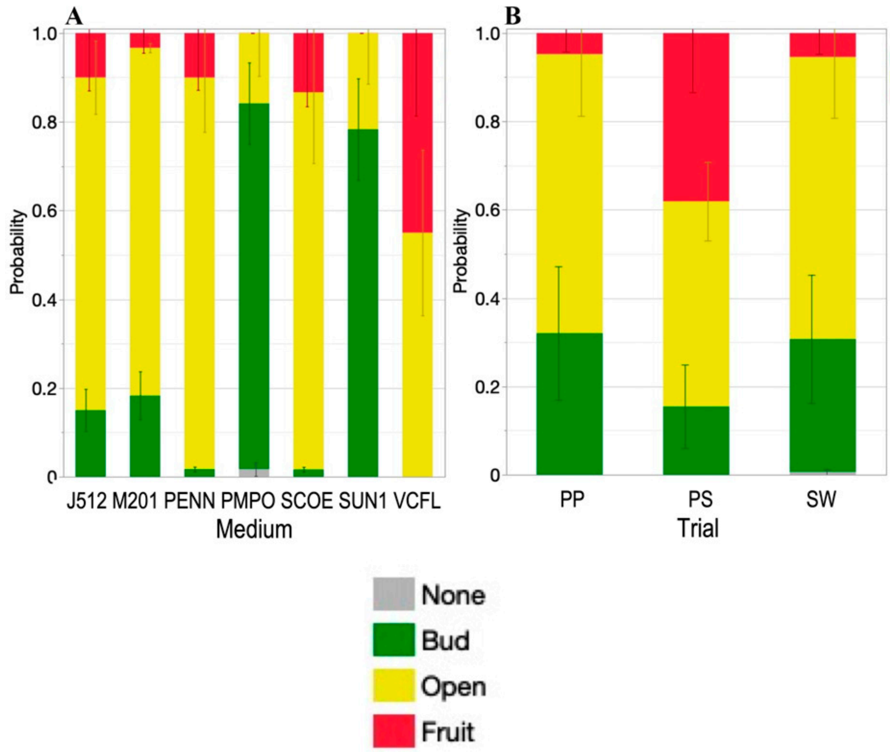

Fig. 3. Probability of plants with no reproductive structures, or at least one bud, open flower, or set fruit 4 weeks after transplanting for tomatoes grown in seven different media during transplant production at three trial locations in Indiana, USA, in 2018. (A) Media means. (B) Trial means. Bars represent probability based on four replications per trial. Error bars represent ±*SE*. J512 = Johnny's 512 Mix; M201 = Premium Flower 201; PENN = Penn Valley Potting Soil; PMPO = Promix MP Organik; SCOE = Seed Catapult; SUN1 = Sunshine No. 1 Natural and Organic; VCFL = Fort Light. See Table 1 for manufacturer and major ingredients of media. PP = Pinney Purdue Agricultural Center, Wanatah, IN, USA; PS = Purdue Student Farm, West Lafayette, IN, USA; SW = Southwest Purdue Agricultural Center, Vincennes, IN, USA.

and so the total nutrient requirement was less than what would be needed for a season-long crop. More importantly, the goal was to avoid unintentionally covering up growing media effects, especially any that might be mediated by soil microbes. Literature reports indicate that soil nutrient levels can influence microbial communities and potentially mask microbe effects on plant growth (Lin et al. 2019; Marschner et al. 2004). If the growing media effects observed in the field in this study were partially mediated by microbes whose influence depends on soil nutrient levels, it is possible that in a field where fertilizers were applied, the differences among media in field tomato growth would not be observed. Additional work is necessary to tease out the relationship between field soil nutrient status and growing media effects.

The results suggest that measuring media EC before seeding could help growers adapt management practices to specific organic media. For example, knowing the negative effect of high EC on germination, a grower using a media with high EC may choose to avoid emergence delays by germinating seeds in a different media with low EC, or may decide to pay close attention to keeping the high EC media moist during emergence and be prepared for emergence to take a little longer.

Given the wide range of plant growth observed in these media that is likely due in part to differences in nutrient supply, it would be useful to identify a method that would indicate the amount of plant-available N, P, and K expected over a production cycle. This kind of test could inform growers about the potential benefits of adding nutrients to media before and during seedling growth. This supports Rogers' (2017) identification of N mineralization dynamics of growing media as an important area for research.

Additional considerations for growers include the wettability of the media. If media does not wet uniformly and easily it is important—especially during the germination stage—to repeatedly apply water to the surface or to subirrigate to ensure the media is fully wet. An objective assessment of media wettability might be a useful way to characterize media.

Conclusions

It is clear that seedling performance from emergence through the transplant stage and into the field differs among growing media permitted for use in certified organic production. The best growing media is likely to differ depending on the plant growth stage evaluated. Without any added nutrients, the media SUN1 and PMPO permitted excellent emergence but seedling growth was poor. VCFL led to the most problems with emergence, but once plants emerged they grew well and performed very well in the field. In the medium SCOE, emergence was excellent; plants also performed well in the greenhouse and after planting to the field. In the media PENN, M201, and J512, plants grew well, but in M201, plants took longer to emerge. Differences in emergence were most easily explained by known effects of EC on emergence: higher EC was associated with delayed and less uniform emergence. It appeared likely that N limited seedling growth and potential for early yield. Based on this research it is not possible to judge how the various media would compare if additional nutrients were added during transplant production.

This evaluation of growing media in multiple trials at different locations supports the following conclusions. Media containing compost are likely to have EC levels high enough to negatively affect emergence, but once emerged, plants may grow well. When no additional nutrients are added, plants grown in media containing compost are likely to be larger and set fruit earlier than plants in media without compost.

In addition to developing media testing for organic production, future research to design plans for supplemental nutrients based on specific growing media characteristics will help growers develop efficient and economical organic transplant production systems. In addition, it is likely that media effects on seedlings as well as on plants in the field are mediated by root-zone microorganisms (Jack et al. 2011). Investigation into these biological interactions is needed to understand how to develop growing media and production practices that use the biology to the best advantage.

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