Optimal Growing Substrate pH for Five *Sedum* Species

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Abstract. To determine the optimal growing substrate pH values for *Sedum* plants, *Sedum album*, *Sedum reflexum* 'Blue Spruce', *Sedum spurium* 'Dragon's Blood', *Sedum hybridum* 'Immergrunchen', and *Sedum sexangulare* were grown in containers using peatmoss and perlite-based substrates at five target pH levels (i.e., 4.5, 5.5, 6.5, 7.5, and 8.5). Optimal pH levels, calculated from dry weight regression models, were 6.32, 6.43, 5.71, 6.25, and 5.91 for *S. album*, *S. reflexum*, *S. spurium*, *S. hybridum*, and *S. sexangulare*, respectively, and 5.95 overall. *Sedum spurium* dry weight varied the most among pH treatments (i.e., 9.5 times greater at pH 6.3 vs. 8.3), whereas *S. reflexum* varied the least (i.e., 1.3 times greater at pH 6.3 vs. 4.4), indicating species-specific growth responses to growing substrate pH. These findings identified a narrow range of optimal growing substrate pH levels within a wider pH range tolerated by five *Sedum* spp. Therefore, by adjusting substrate pH to optimal levels, *Sedum* growth can be maximized.

Sedum plants have been used in rock gardens and other landscape settings as groundcovers for many years. However, the high demand for *Sedum* plants only started recently when green roof installations became increasingly popular in North America (Getter and Rowe, 2007; Monterusso et al., 2005). Green roof installations often require green roof plant producers to provide plant materials with only a short timeframe from ordering to delivery. Understanding the ideal growing conditions for *Sedum* will allow for efficient *Sedum* plant production to meet the increasing industry demand.

Growing substrate pH influences plant growth and performance, and different plant species have optimal substrate pH ranges that are unique (Reed, 1996). Substrate pH levels below or above optimal ranges may reduce plant root and shoot growth, influence nutrient uptake, and may even cause plant failure (Marschner, 1986).

Many *Sedum* species are able to grow in a wide range of soil conditions (Stephenson, 1994) and even under extreme environments such as on the edge of cement driveways. However, a wide tolerance of soil conditions, including different soil pH levels, does not necessarily indicate plants thrive in a wide

substrate pH range. Given that *Sedum* plants are in high demand for green roof installations, there is an urgent need for recommendations regarding optimal growing conditions, including growing substrate pH, for *Sedum* species.

The objective of this study was to evaluate the hypothesis that *Sedum* species have optimal growing substrate pH levels or ranges. Specifically, this study aimed to determine the optimal growing substrate pH levels or ranges for the growth of five *Sedum* species commonly used in green roof installations.

Materials and Methods

Plant material and treatments. The research was conducted under greenhouse conditions with air temperatures of 27 °C day/22 °C night $\pm$ 2 °C, and 55% relative humidity, with roof shade curtains programmed to close and open when global radiation was greater than 500 W·m⁻² and less than 150 W·m⁻², respectively. The following five common green roof *Sedum* species were evaluated for plant growth response to substrate pH: *Sedum album*, *Sedum reflexum* 'Blue Spruce', *Sedum spurium* 'Dragon's Blood', *Sedum hybridum* 'Immergrunchen', and *Sedum sexangulare*.

Sedum plants were propagated directly into pH-adjusted substrate by planting 4-cm cuttings. Three cuttings of one species were planted per container (400-mL round, green plastic pots, 10 cm top and 6.8 cm bottom diameters) and thinned to one representative cutting per container once rooted. The growing substrate was a mixture of 80% Canadian sphagnum peat and 20% perlite (Therm-O-Rock East, New Eagle, PA). A 60-L batch of substrate was mixed and 250 g (i.e., 0.67 g nitrogen/L) of Polyon Homogenous NPK

plus Minors 16N–2.6P–10.8K, 3–4 month controlled release fertilizer (Agrium Advanced Technologies, Brantford, Ontario, Canada) was incorporated evenly. To adjust the substrate pH to five target treatment levels (i.e., 4.5, 5.5, 6.5, 7.5, and 8.5), hydrated lime (61.1% CaOH₂, 37.1% MgOH₂, 0.4% silica and insoluble components, 0.4% iron and aluminum oxides, 0.3% sulfur trioxide, 140 calcium carbonate equivalency; Graymont Dolime Spray Lime, Genoa, OH) was added at rates pre-determined by regression analysis following laboratory titrations (data not shown). To reduce experimental error in this study, rates of hydrated lime were separately incorporated into pre-measured volumes of substrate for each container, and containers were filled and uniformly compacted. Substrate-filled containers were placed in the greenhouse and covered with translucent white shade cloth for 7 d before planting to facilitate the pH-adjustment reaction. Plants were watered as needed for the duration of the experiment using deionized water (pH 7.0 $\pm$ 0.5). Containers were spaced $\approx$ 3 cm apart in a completely randomized design on the greenhouse bench surrounded by a border of identical, planted, non-treatment containers to reduce edge effects. There were five replicates (i.e., containers) and five *Sedum* species for each substrate pH level. Treatment containers were re-randomized biweekly to reduce location effects.

Data collection. To ensure treatment pH and electrical conductivity (EC) conditions were within the target range for the duration of the experiment, a pour-through extraction, adapted from Wright (1986), was conducted at 1, 3, 5, and 6 weeks after planting. Leachate obtained from the pour-through extraction was analyzed using a portable pH and EC meter (Oakton PC 300; Oakton Instruments, Vernon Hills, IL). At 3 and 6 weeks after planting, plant height, number of shoot branches, and plant width in two perpendicular directions (for calculating elliptical plant canopy area) were measured. Six weeks after planting, photographs were taken before plants were destructively harvested and fresh weight of the aboveground tissue was measured. Aboveground tissue was placed in paper bags in a drying oven at 60 °C and dry weight was measured after 7 d once a constant weight was achieved.

Dried aboveground tissue was ground to fit through a 1-mm screen, dry-ashed in a 450 °C oven, digested using a HCl solution, and analyzed using the SNL-055 method to evaluate nitrogen, phosphorus, potassium, magnesium, calcium, copper, zinc, manganese, boron, and iron in plant tissue using an inductively coupled plasma optical emission spectrometer (University of Guelph Laboratory Services, Guelph, Ontario, Canada).

Statistical analysis. All data sets were analyzed using GraphPad Prism Version 5.03 (GraphPad Software Inc., La Jolla, CA). The Shapiro-Wilk test was used to test data for normality. A one-way analysis of variance with a Tukey's multiple comparison test was conducted for pH, EC, plant growth, and tissue nutrient data. Regression analyses

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were used to relate plant growth and tissue nutrient data to substrate pH and to estimate parameters for the best-fit regression model (linear or quadratic). Regression models for dry weight were used to determine optimal pH for maximum plant growth per *Sedum* spp. and estimate the pH range at which 90% of the maximum plant growth would occur. Pearson correlation coefficients were calculated to compare tissue dry weight with nutrient content. Treatment effects were evaluated using a significance level of $P < 0.05$.

Results

Substrate pH and electrical conductivity. The combination of the peat-perlite substrate and increasing amounts of hydrated lime did produce substrate pH levels within the targeted treatment range, and the pH range was maintained for the duration of the experiment (Table 1). However, within each pH treatment, measured pH significantly differed among some time intervals (Table 1). Measured pH values were used to describe pH treatment effects.

Substrate EC values were significantly different among pH treatments at 1, 5, and 6 weeks after transplanting, but not at 3 weeks after planting (Table 2). Although substrate EC changed over the duration of the study, EC levels remained adequate for *Sedum* growth.

Growth response to pH. Visual differences in plant growth were observed for all five *Sedum* species 6 weeks after planting (Fig. 1). The best overall growth, considering all species, was observed in the 5.4 and 6.4 pH

treatments; however, responses varied by species and growth characteristic (Fig. 2). Dry weight of *S. album* was greater in the 6.4 pH treatment than the 4.4 and 8.2 pH treatments. *Sedum album* fresh weight, branch number, and plant area were greater in the 6.4 and 7.2 pH treatments than the 8.2 pH treatment. No difference among treatments was observed for *S. album* plant height. Dry and fresh weights of *S. reflexum* were greater for the 5.4, 6.4, and 7.2 pH treatments than the 4.4 pH treatment. *Sedum reflexum* branch number and plant area followed this trend, but no significant difference in plant height among pH treatments was observed. For *S. spurium*, all vegetative characteristics were significantly greater in the 5.4 and 6.4 pH treatments than the 7.2 and 8.2 pH treatments. All *S. hybridum* vegetative traits were significantly greater in the 6.4 than the 4.4 and 8.2 pH treatments. Although *S. sexangulare* plant area was not significantly different among pH treatments, dry weight was greater in the 6.4 than the 7.2 and 8.2 pH treatments. Similarly, *S. sexangulare* fresh weight and plant height were greater in the 6.4 than the 8.2 pH treatment. *Sedum sexangulare* branch number was greatest in the 6.4 pH treatment but was not significantly different among all other pH treatments. Overall, the poorest plant growth occurred in the 8.2 pH treatment, characterized by four of five *Sedum* species (i.e., *S. album*, *S. spurium*, *S. hybridum*, and *S. sexangulare*) producing the lowest dry weight in this pH treatment (Fig. 2). The magnitude of difference in growth among pH treatments was the greatest for *S. spurium* and least for *S. reflexum* with 9.5 and 1.7 times greater dry weight in the 6.4 vs. the 8.2 and the

6.4 vs. the 4.4 pH treatments, respectively. Dry weights for *S. album* and *S. hybridum* were 2.9 and 3.0 times greater in the 6.4 vs. the 8.2 pH treatment and 1.4 times greater for *S. sexangulare* in the 6.4 vs. the 7.2 pH treatment.

For each of the five *Sedum* spp., mean dry weight among pH treatments followed a quadratic response, as identified by regression analysis (Fig. 2). A quadratic response to measured substrate pH was also observed for fresh weight and plant area for all five *Sedum* species as well as plant height and branch number for *S. album*, *S. reflexum*, *S. spurium*, and *S. hybridum* (Fig. 2). Dry weight measurements were selected to calculate the optimal pH range for maximum *Sedum* growth, because dry weight best incorporated all aspects of plant growth.

From the regression model, the calculated optimal pH resulting in maximum plant growth (i.e., dry weight) for all species combined was 5.95. Optimal pH levels were lowest for *S. spurium* (5.71); midrange for *S. album* (6.32), *S. hybridum* (6.25), and

Table 1. Growing substrate pH for five *Sedum* species over 6 weeks.

Weeks	Target pH					P ^y
	4.5	5.5	6.5	7.5	8.5	
	Actual pH per target pH treatment ^z					
1	4.38 ± 0.03 a	5.45 ± 0.05 a	6.63 ± 0.04 a	7.67 ± 0.03 a	8.35 ± 0.03 a	***
3	4.36 ± 0.02 a	5.37 ± 0.05 ab	6.54 ± 0.04 a	7.40 ± 0.04 b	8.25 ± 0.04 a	***
5	4.39 ± 0.06 a	5.21 ± 0.07 b	6.24 ± 0.06 b	6.87 ± 0.05 c	8.10 ± 0.05 b	***
6	4.55 ± 0.05 b	5.45 ± 0.09 a	6.09 ± 0.06 c	6.94 ± 0.07 c	8.31 ± 0.05 a	***
All ^x	4.42 ± 0.04	5.37 ± 0.06	6.37 ± 0.12	7.22 ± 0.19	8.24 ± 0.06	

^zData followed by the same letter within the same column are not significantly different at $P < 0.05$. Data are means of 25 replications ± SE.

^y***Significance at $P < 0.0001$ within week intervals among target pH treatments.

^xData are means of 6 weeks.

Table 2. Growing substrate electrical conductivity (EC) for five *Sedum* species over 6 weeks.

Weeks	Growing substrate pH					P ^y
	4.4	5.4	6.4	7.2	8.2	
	Growing substrate EC (dS·m ⁻¹) per pH treatment ^z					
1	2.90 ± 0.17 ab	2.67 ± 0.10 a	2.90 ± 0.18 a	2.88 ± 0.16 a	2.24 ± 0.85 b	**
3	3.15 ± 0.25 a	2.98 ± 0.14 a	2.73 ± 0.16 a	2.96 ± 0.23 a	2.75 ± 0.17 a	NS
5	2.56 ± 0.26 b	2.14 ± 0.20 b	1.73 ± 0.25 b	2.60 ± 0.26 a	2.71 ± 0.19 a	*
6	1.94 ± 0.18 c	1.21 ± 0.15 c	0.98 ± 0.17 c	1.68 ± 0.19 b	2.10 ± 0.15 b	***
All ^x	2.64 ± 0.26	2.25 ± 0.39	2.08 ± 0.45	2.53 ± 0.29	2.45 ± 0.16	

^zData followed by the same letter within the same column are not significantly different at $P < 0.05$. Data are means of 25 replications ± SE.

^yNS, *, **, *** Nonsignificant, or significant at $P < 0.05$, 0.01, and 0.0001, respectively, within week intervals among pH treatments.

^xData are means of 6 weeks.

Fig. 1. Depiction of five *Sedum* species grown under a range of substrate pH levels 6 weeks after planting in the greenhouse. Substrate pH levels are indicated below images for each representative plant per treatment and are means of five replications over 6 weeks.

Fig. 2. The response of five plant growth attributes to growing substrate pH for *Sedum album* (●), *S. reflexum* 'Blue Spruce' (■), *S. spurium* 'Dragon's Blood' (○), *S. hybridum* 'Immergrunchen' (□), and *S. sexangulare* (◆) measured 6 weeks after planting. Data are means of five replications $\pm$ SE. Lines indicate calculated regression relationships are significant at $P < 0.05$.

S. sexangulare (5.91); and highest for *S. reflexum* (6.43; Table 3). In addition, the pH range calculated to result in 90% of the maximum plant growth was from 5.22 to 6.69 overall. *Sedum sexangulare* (i.e., 4.81 to 7.01) and *S. spurium* (i.e., 4.95 to 6.48) species had the largest and smallest pH ranges, respectively (Table 3).

In addition to plant growth, differences in plant tissue coloration occurred among

Table 3. *Sedum* plant growth (i.e., dry weight measured 6 weeks after planting) response to growing substrate pH.

<i>Sedum</i> species	Regression model	R^2	P^z	pH_{Opt}^y	90% lower limit for pH_{Opt}^x	90% upper limit for pH_{Opt}^x
<i>S. album</i>	$Y = -6.3 + 2.4X - 0.19X^2$	0.50	**	6.32	5.50	7.14
<i>S. reflexum</i> Blue Spruce	$Y = -4.7 + 1.8X - 0.14X^2$	0.59	***	6.43	5.55	7.31
<i>S. spurium</i> Dragon's Blood	$Y = -7.5 + 3.2X - 0.28X^2$	0.64	**	5.71	4.95	6.48
<i>S. hybridum</i> Immergrunchen	$Y = -11.8 + 4.5X - 0.36X^2$	0.68	***	6.25	5.46	7.04
<i>S. sexangulare</i>	$Y = -2.5 + 1.3X - 0.11X^2$	0.29	*	5.91	4.81	7.01
Overall	$Y = -6.3 + 2.5X - 0.21X^2$	0.36	**	5.95	5.22	6.69

*, **, ***Significant at $P < 0.05$, 0.01, and 0.0001, respectively.

^yOptimal substrate pH level (pH_{Opt}) calculated as the maximum of the regression model.

^xSubstrate pH range, which would yield 90% of the maximum plant growth, as calculated from the regression model.

pH treatments for some *Sedum* species as early as 3 weeks after planting. In particular, some *S. album* and *S. sexangulare* plants in the 4.4 pH treatment had slightly yellowish green shoot tips. Also, some *S. spurium* plants grown under pH 7.2 and 8.2 showed a reddish purple stem and leaf coloration compared with plants grown at all other pH levels.

Tissue nutrient composition. Differences in tissue nutrient contents among substrate pH treatments were observed for some macronutrients but were species-specific (Table 4). No difference in percent phosphorus (P) was observed for *S. album* or *S. spurium* tissue among pH treatments, but percent P for *S. reflexum* and *S. sexangulare* tissue in the 5.4, 6.4, and 7.2 pH treatments was higher than in the 8.2 pH treatment. The percent P for *S. hybridum* tissue was higher in the 4.4 and 5.4 pH treatments than the 8.2 pH treatment. No difference in percent potassium (K) was observed for *S. spurium* or *S. hybridum* tissue among growing substrate pH treatments, although in *S. sexangulare* tissue, percent K was higher in the 7.2 than the 4.4 pH treatment. For all species, percent magnesium (Mg) was higher in the 8.2 than the 4.4, 5.4, and 6.4 pH treatments. For *S. spurium* and *S. hybridum* tissue, the percent calcium (Ca) was the highest in the 6.4 and 7.2 pH treatments and higher in the 6.4 and 7.2 pH treatments than 4.4 and 8.2 pH treatments for *S. album* tissue. The percent Ca for *S. sexangulare* tissue was the highest in the 5.4, 6.4, and 7.2 pH treatments. *Sedum reflexum* tissue followed the same trend. Some species-specific differences for tissue micronutrient concentrations were observed among pH treatments (Table 4).

Tissue dry weight was positively correlated with P content for *S. album* and percent Ca and zinc for *S. reflexum* when all pH treatments were combined ($r = 0.94$, 0.96, and 0.93, respectively). No other significant correlations were observed between dry weight and nutrient content for the *Sedum* spp. in this study.

Discussion

Results from the current study clearly outlined how growing substrate pH influenced

Sedum plant growth. Growth responses indicated a preferred pH level for *Sedum*, because plant growth was greater within the preferred pH range compared with plant growth above or below this range. In addition, different *Sedum* species had different optimal pH levels for maximum growth as measured by dry weight. The overall optimal pH was 5.95 and the optimal pH values for individual *Sedum* species were 6.32, 6.43, 5.71, 6.25, and 5.91 for *S. album*, *S. reflexum*, *S. spurium*, *S. hybridum*, and *S. sexangulare*, respectively. Considering the magnitude of reduced growth between optimal and unfavorable pH levels (i.e., dry weight reduction of up to 9.5 times), substrate pH should be considered a critical factor for *Sedum* plant growth.

No other published systematic research was found to identify pH preferences in growing substrates for *Sedum* plants. Literature discussing growing substrate pH preferences of *Sedum* species has been limited to ecological observations of North American *Sedum* spp. (Clausen, 1975) and more specifically for *S. nuttallianum* and *S. pulchellum* (Crow and Ware, 2007; Ware, 1990) as well as for *S. rubrotinctum* grown in a nutrient solution (Gudrupa et al., 2002). Reports of soil pH levels in native environments for *Sedum* spp. (Clausen, 1975) does not necessarily indicate optimal pH levels for *Sedum* growth. The findings of the current study form a new point of reference to guide decisions in maximizing *Sedum* growth during production and plant maintenance in landscape and green roof industries.

The current study used a peat-based substrate to evaluate *Sedum* growth, which can be directly applied to *Sedum* propagation and production in soilless organic substrates. Many green roof substrates resemble mineral soils (FLL, 2008) and may have slightly higher optimal pH levels for plant growth compared with soilless organic substrates. We conducted a preliminary study using a commonly available commercial green roof substrate (with a high mineral content); however, the high pH value and high acid-buffering capacity of the commercial substrate limited our ability to appropriately adjust the substrate to lower pH levels. The difficulty of adjusting high pH mineral

Table 4. Tissue nutrient content² for five *Sedum* species grown under five growing substrate pH levels.

Tissue nutrient	Growing substrate pH ²				
	4.4	5.4	6.4	7.2	8.2
<i>S. hybridum</i> 'Immergrünchen'					
P (%)	0.651 a	0.515 ab	0.436 b	0.364 bc	0.244 c
K (%)	2.470	2.348	2.174	2.196	2.028
Mg (%)	0.604 d	0.663 cd	0.745 bc	0.846 ab	0.858 a
Ca (%)	1.172 c	1.593 b	1.966 a	2.022 a	1.078 c
Cu (μg·g ⁻¹)	12.64 a	10.55 ab	10.01 ab	8.790 bc	6.190 c
Zn (μg·g ⁻¹)	97.41 a	72.26 ab	78.65 a	77.10 a	49.35 b
Mn (μg·g ⁻¹)	178.0 a	98.85 b	79.30 b	66.45 bc	33.16 c
B (μg·g ⁻¹)	31.45 a	19.71 b	13.76 c	10.37 c	9.77 c
Fe (μg·g ⁻¹)	71.45 a	56.46 b	47.98 b	51.08 b	44.18 b
<i>S. sexangulare</i>					
P (%)	0.389 ab	0.517 a	0.493 a	0.573 a	0.226 b
K (%)	1.983 b	2.794 ab	2.708 ab	3.863 a	3.167 ab
Mg (%)	0.404 d	0.579 c	0.718 b	0.847 ab	0.953 a
Ca (%)	0.696 c	1.390 a	1.650 a	1.560 a	1.080 b
Cu (μg·g ⁻¹)	13.06 ab	16.67 ab	13.79 ab	19.95 a	9.141 b
Zn (μg·g ⁻¹)	54.38 b	101.3 ab	91.59 ab	135.6 a	73.21 ab
Mn (μg·g ⁻¹)	110.6 a	102.3 a	110.5 a	98.60 a	51.86 b
B (μg·g ⁻¹)	20.73 ab	22.66 a	15.55 bc	20.19 ab	11.21 c
Fe (μg·g ⁻¹)	131.4	98.48	97.20	121.0	98.98
<i>S. spurium</i> 'Dragon's Blood'					
P (%)	0.349	0.393	0.315	0.398	0.241
K (%)	2.725	3.017	2.521	— ^x	3.135
Mg (%)	0.507 c	0.605 bc	0.765 b	—	0.961 a
Ca (%)	0.946 c	1.346 b	1.864 a	1.825 a	1.062 bc
Cu (μg·g ⁻¹)	12.150	7.980	7.340	—	9.150
Zn (μg·g ⁻¹)	73.24 b	93.21 ab	129.0 a	107.3 ab	80.57 b
Mn (μg·g ⁻¹)	167.90 a	86.00 b	96.34 b	—	51.16 b
B (μg·g ⁻¹)	20.70 a ^v	17.94 ab	14.94 ab	10.80 b	14.93 ab ^v
Fe (μg·g ⁻¹)	92.31	79.65	64.30	—	60.26
<i>S. album</i>					
P (%)	0.428	0.531	0.565	0.512	0.363
K (%) ^y	—	3.390 ^w	3.583	—	—
Mg (%)	0.511 d	0.651 cd	0.818 bc	0.984 ab	1.093 a
Ca (%)	0.943 d	1.702 bc	2.143 ab	2.476 a	1.460 cd
Cu (μg·g ⁻¹)	18.40	25.06	18.00	15.63	30.51
Zn (μg·g ⁻¹)	39.33 b	94.22 ab	129.4 a	87.69 ab	61.70 ab
Mn (μg·g ⁻¹) ^y	—	130.5 ^w	259.3	—	—
B (μg·g ⁻¹)	23.42	22.13 ^v	17.80 ^w	12.03	17.42
Fe (μg·g ⁻¹) ^y	—	83.49 ^w	100.2	—	—
<i>S. reflexum</i> 'Blue Spruce'					
P (%)	0.378 ab	0.545 a	0.518 a	0.472 a	0.189 b
K (%) ^y	—	2.840 ^v	3.300	—	2.169 ^w
Mg (%)	0.468 d	0.575 cd	0.690 bc	0.831 b	1.080 a
Ca (%)	0.934 c	1.844 ab	2.159 ab	2.366 a	1.555 bc
Cu (μg·g ⁻¹)	18.66	14.14	11.97	18.03	14.96
Zn (μg·g ⁻¹)	48.81 c	85.4 abc	114.7 ab	122.7 a	73.87 bc
Mn (μg·g ⁻¹) ^y	—	124.2 ^v	117.6	—	40.30 ^w
B (μg·g ⁻¹)	26.65	29.19 ^v	22.09 ^w	13.48	9.450 ^v
Fe (μg·g ⁻¹) ^y	—	74.32 ^v	70.43	—	53.76 ^w

²Data are means of three replicates; data in rows followed by the same lowercase letters are not significantly different $P < 0.05$.

^yTukey's multiple comparison test not performed due to missing data.

^{x,w,v}n = 0, n = 1, and n = 2, respectively; low sample sizes as a result of complications during tissue analysis. P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; Cu = copper; Zn = zinc; Mn = manganese; B = boron; Fe = iron.

growing substrates to reach an array of desired lower pH levels may account for the lack of published data on optimal green roof substrate pH ranges for *Sedum* and other plant species. Optimal pH ranges for the five *Sedum* species in the current study could be slightly higher when grown in mineral soils or green roof substrates with a high mineral material content. However, further research is needed to verify optimal pH levels

for *Sedum* species in different growing substrates, especially in substrates containing a high percentage of mineral components when grown for a longer period.

Although substrate EC levels were significantly different over time for the duration of the current study, the overall mean EC for all treatments was still within the range required for the majority of container-grown plants (i.e., 1.0 to 3.5 dS·m⁻¹; Cavins et al., 2000),

except for the slightly low level observed in the 6.4 pH treatment 6 weeks after planting. The observed increase in substrate EC between 1 and 3 weeks after planting was likely the result of nutrient release as caused by warm and moist conditions in the growing substrate. The observed reduction in EC over time, especially within the middle pH range, could have been caused by nutrient uptake in response to faster plant growth in these pH treatments. Measured EC values indicate that the difference in *Sedum* species' growth among pH treatments was not the result of salt toxicity or overall lack of nutrients in the substrate.

Although nutrient availability was not the focus of the current study, pH-influenced nutrient availability should not be discounted as one cause for the differences in *Sedum* plant growth. In soilless substrates, the recommended optimum pH range for nutrient availability is 5.6 to 6.2 (Reed, 1996). Below this range, availability of Ca and Mg decline, and above this range, P and other minor nutrients become decreasingly available to plants. Observations of light yellowish green shoot tips suggested Mg deficiency symptoms for some *S. sexangulare* and *S. album* plants grown in the 4.4 pH treatment. Tissue Mg concentrations in the 4.4 pH treatment were the lowest for *S. sexangulare* and among the lowest for *S. album* among the pH treatments. In the 7.2 and 8.2 pH treatments, the typical red color of *S. spurium* leaves and stems was visually darker than in the other pH treatments. Because *S. spurium* tissue P concentration did not differ among pH treatments, the dark red tissue in 7.2 and 8.2 pH treatments might have resulted from a concentration of red pigments, as a result of stunted *S. spurium* growth, rather than P deficiency. However, further research is needed to determine factors influencing color responses and identify nutrient deficiency symptoms in *Sedum* spp. Overall, growth of *Sedum* species clearly showed a response to growing substrate pH with different species having different optimal pH levels. Therefore, it is beneficial to adjust the substrate pH to the optimal range for individual *Sedum* species to promote maximum growth. The current study has identified the optimal pH for maximum growth for five *Sedum* species, which can be used to guide production and maintenance of *Sedum* species for horticultural applications including green roof plantings.

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