pH Buffering in Pine Bark Substrates as a Function of Particle Size

Magdalena Pancerz

The Ohio State University, Ohio Agricultural Research and Development Center, 1680 Madison Avenue, Wooster, OH 44691

James E. Altland

Application Technology Research Unit, U.S. Department of Agriculture Agricultural Research Service, Agricultural Engineering Building, 1680 Madison Avenue, Wooster, OH 44691

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Abstract. Stability of substrate pH in container-grown crops is important for proper nutrient management. The objective of this research was to determine the pH buffering capacity of pine bark substrates as a function of particle size and compare those results to sphagnum peat. The weight equivalent of 100 cm³ for fine, medium, and coarse pine bark and sphagnum peat, either as a whole or partitioned into several particle size ranges, was placed in a 250-mL glass jar and filled with 100 mL of an acid or base solution ranging from 0 to 50 meq·L⁻¹ in 10 meq·L⁻¹ increments. After 24 hours, pH was measured. An experiment was also conducted in the greenhouse. The weight equivalent of 500 cm³ of sphagnum peat, fine pine bark, or coarse pine bark was filled into 10-cm plastic pots and irrigated with one of the following: tap water or 10 meq·L⁻¹ of HCl, NaOH, H₂SO₄, or KHCO₃ and with or without a water soluble fertilizer. Substrate pH was determined 4 and 8 weeks after potting using the pour-through method. In all experiments, sphagnum peat had less buffering capacity than pine bark against pH changes from acidic solutions, whereas pine bark had less buffering capacity than sphagnum peat to pH changes from basic solutions. Substrate pH buffering in pine bark increased with decreasing particle size, whereas pH buffering in sphagnum peat was less responsive to particle size. These results will help growers and substrate manufacturers understand how substrate components contribute to pH management during crop production.

Stability of substrate pH is an important factor in managing nutrition of container-grown crops. Some nursery and greenhouse crops have specific pH requirements. Walden and Epelman (1988) reported increased Japanese boxwood (*Buxus microphylla* Siebold & Zucc. var. *japonica*) root and shoot growth with increasing dolomitic lime (DL) rate and concomitant increase in pH. The increase in growth was attributed to a decrease in the ammonium (NH₄⁺)-to-nitrate (NO₃⁻) ratio because higher pH substrates resulted in more rapid nitrification of NH₄⁺ to NO₃⁻. Argo and Fisher (2002) identified three groups of floriculture crops based on pH requirements: a petunia group that is prone

to iron deficiency at high pH, a general group recommended to be grown at pH 5.8 to 6.2, and a geranium group prone to iron or manganese toxicity at low pH. Crop preference for pH specificity could be related to the crop's native environment. For example, Harvey et al. (2004) reported that 'Aureola' hakonechloa [*Hakonechloa macra* (Makino) Honda] grew best in a 3 pine bark: 2 sphagnum peat: 1 sand (by volume) substrate with no DL amendment (pH 4.5). They speculated this favorable response was due to the plant's adaptation to the low pH soil found in the mesic, forested mountains of its native range in Hakone, Japan.

Substrate pH of nonamended pine bark is generally 4.1 to 5.1 (Altland and Jeong, 2016) and is commonly increased using DL before potting. The two primary factors that increase or decrease pH after potting and during the production cycle are irrigation water alkalinity or ammoniacal fertilizers, respectively. Irrigation water alkalinity is a measure of carbonates, bicarbonates, and hydroxyl ions in solution. It increases substrate pH when these compounds, predominantly bicarbonate ions, react with the substrate solution to consume hydrogen ions and thus increase pH (HCO₃⁻ + H⁺ <=> H₂CO₃ <=> CO₂ + H₂O). Irrigation water pH has relatively little effect on substrate pH compared with irrigation water alkalinity. Ramirez and Altland

(2018) reported that a 0.0001 mM KOH solution with high pH (8.23) and low alkalinity (10.0 mg·L⁻¹ CaCO₃) did not increase substrate pH over 3 months, whereas a 0.005 M KHCO₃ solution with similar pH (8.28) but high alkalinity (275 mg·L⁻¹ CaCO₃) increased substrate pH by more than 2 units after 3 months.

Many fertilizers acidify container substrates. Johnson et al., (2013) showed that fertilizer calcium carbonate equivalent (CCE) was effective in predicting the overall impact of a fertilizer on substrate pH. Moreover, the authors (Johnson et al., 2013) noticed that a simple estimation of the acidity or basicity of a fertilizer could be determined by nitrogen form and concentration. Fertilizers containing urea (CH₄N₂O-N) or ammonium (NH₄⁺-N) nitrogen decrease pH by nitrification of NH₄⁺ to NO₃⁻, as well as H⁺ release during root uptake of NH₄⁺ to maintain charge balance (Lang and Elliott, 1991). Albano et al. (2017) showed that substrate pH of a 9 Florida peat: 9 pine bark: 2 sand substrate fertilized with a controlled release fertilizer (Osmocote 19N-2.6P-9.9K), containing 9% NH₄⁺-N and 10% NO₃⁻-N, decreased over time when irrigation alkalinity ranged from 50 to 150 mg·L⁻¹ CaCO₃.

The ability of a substrate to resist change in pH over time is termed pH buffering capacity. Buffering capacity can be affected by substrate components. Rippey et al. (2005) measured buffering capacity as the amount of base (mol·kg⁻¹) required to raise the pH of a peat sample from 5.4 to 6.2 and showed that buffering capacity varied among 64 sphagnum peat samples collected from bogs in Alberta, Canada. Despite the importance of substrate pH on crop growth in pine bark substrates (Altland and Jeong, 2016), there is no scientific literature on the ability of pine bark to buffer changes in pH. Therefore, the objective of this research was to compare the pH buffering capacity of pine bark and its particle size fractions to nursery-grade sphagnum peat.

Materials and Methods

Three different commercial pine bark (*Pinus taeda* L.) substrates marketed as having different physical properties were obtained (Pacifi Organic, Henderson, NC) and compared with sphagnum peat (Conrad Fafard Inc., Agawam, MA) for pH buffering capacity. The three pine bark substrates were subjectively labeled as being fine, medium, or coarse (Table 1), and all were screened on site and stored for less than 4 weeks. Pine bark samples were collected in May 2018 from the bark supplier during a site visit. From each bark pile, the top 10 cm was scraped away at three locations within the pile, and ≈30 L of pine bark was collected from each location, for a total volume of 90 L. Pine bark samples were transported back to Wooster, OH, in 117-L plastic containers and stored in a cooler at 4 °C until analyzed.

Substrate physical properties. Particle size distribution of each sample was determined

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M.P. is a Visiting Scholar.

J.E.A. is a Research Horticulturist.

J.E.A. is the corresponding author. E-mail: james.altland@usda.gov.

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using $\approx 100 \text{ cm}^3$ of oven-dried substrate (60°C) and passing it through sieves sized 19.0, 12.5, 6.3, 4.0, 2.8, 2.0, 1.4, 1.0, 0.71, 0.50, 0.35, 0.25, 0.18, and 0.11 mm. Particles $\leq 0.11 \text{ mm}$ were collected in a pan. Sieves and the pan were shaken for 3 min with a RX-29/30 Ro-Tap sieve shaker (278 oscillations/min, 150 taps/min; W.S. Tyler, Mentor, OH). Three replicate samples for each material were analyzed. Particle size distributions were subjected to multivariate analysis of variance (ANOVA) to determine whether distributions differed as a whole, then were analyzed by univariate ANOVA within each sieve size. Means were separated within a sieve size using Fisher's protected least significance difference test, where $\alpha = 0.05$.

Pine bark and sphagnum peat samples were packed in 347-cm^3 aluminum cores (7.6 cm tall by 7.6 cm i.d.) according to methods described by Fonteno and Bilderback (1993). There were three replications for each substrate. Aluminum cores were attached to North Carolina State University Porometers (Horticultural Substrates Laboratory, North Carolina State University, Raleigh, NC), then saturated and drained for determination of air space (AS). Cores were weighed, oven dried for 4 d at 110°C , and weighed again to determine container capacity (CC). Total porosity (TP) was calculated as the sum of AS and CC. Bulk density (D_b) was determined using the oven dried (110°C) substrate. Data were subjected to ANOVA to compare sphagnum peat and the three pine bark substrates.

pH buffering of substrate type. The weight equivalent of 100 cm^3 of each pine bark and sphagnum peat sample was determined by filling a graduated cylinder with each substrate individually and measuring the mass of $\approx 100 \text{ cm}^3$. Three replications of each substrate type were then weighed, placed into 250-mL glass jars, and 100 mL of an acid or base solution was added. Acid and base solutions were prepared with hydrochloric acid (HCl) and sodium hydroxide (NaOH),

respectively, at concentrations ranging from 0 to $50 \text{ meq}\cdot\text{L}^{-1}$ in $10 \text{ meq}\cdot\text{L}^{-1}$ increments. Glass jars were sealed with lids and stirred for 10 min using a digital oscillator (Thermolyne Big Bill, Hogentogler & Co. Inc., Columbia, MD) at 350 oscillations per minute. The stirring procedure was repeated after 24 h and pH (Mettler Toledo MA235 pH/Ion Analyzer, Columbus, OH) was measured immediately after stirring. Resulting pH was fitted to a log-logistic function $\text{pH} = y_0 + a / \{1 + \exp[-(x - x_0)/b]\}$, where y_0 represents the lowest pH value of the substrate incurred by exposure to acidic solution, $y_0 + a$ represents the maximum pH value, b is a scaling factor such that the lower the value the more steep the slope transitioning from y_0 to $y_0 + a$, and x_0 is the acid/base concentration ($\text{meq}\cdot\text{L}^{-1}$) at which the sigmoid curve changes from convex to concave (i.e., the inflection point). For purposes of curve fitting, $\text{meq}\cdot\text{L}^{-1}$ acid were expressed as negative values, and $\text{meq}\cdot\text{L}^{-1}$ base were expressed as positive values (Fig. 1). The experiment was repeated once.

pH buffering by particle size fraction. Sphagnum peat and pine bark each were screened to three particle size fractions that represent the range of particles typically found in these substrates, including 0.18 to 0.25 mm, 0.71 to 1.0 mm, and 2.8 to 4.0 mm. Next, two replications of each substrate and particle size fraction were mixed and pH was measured as previously described, except a weight equivalent to 20 cm^3 was placed in a 50-mL conical tube (Falcon Plastics, Brookings, SD) and filled with 20 mL of an acid or base solution. A smaller volume of substrate was used for each sample due to the difficulty in screening the bark to very narrow particle size ranges. The experiment was repeated.

Greenhouse experiment. The fine and medium pine barks, along with the sphagnum peat evaluated in the first experiment, were evaluated for pH buffering capacity in a greenhouse validation study. Substrates were premixed with a dry media surfactant (Aqua-Gro 2000M; Aquatrols Corp. of America,

Inc., Paulsboro, NJ) at $0.5 \text{ g}\cdot\text{L}^{-1}$ substrate. Ten-centimeter plastic pots ($\approx 600 \text{ cm}^3$ volume) were filled with a weight equivalent of 500 cm^3 of each substrate and fully saturated with tap water. Six treatments solutions were applied three times per week with 100 mL solution added per pot each time. The six solutions consisted of tap water alone or tap water mixed with $10 \text{ meq}\cdot\text{L}^{-1}$ HCl or NaOH, or tap water mixed with $100 \text{ mg}\cdot\text{L}^{-1}$ N from a water soluble fertilizer (20N-4.4P-16.6K-0.15 Mg, 0.02B-0.01Cu-0.1Fe, 0.05Mn-0.01Mo-0.05Zn) alone or additionally with $10 \text{ meq}\cdot\text{L}^{-1}$ of sulfuric acid (H_2SO_4) or potassium bicarbonate (KHCO_3). The water-soluble fertilizer was acidic, with a reported calcium carbonate equivalency of 200 kg per metric ton. Every substrate and solution combination consisted of eight single pot replicates. Substrate pH was determined initially for tap water control pots only and for all pots 4 and 8 weeks after potting using a modified pour-through method. Pots were watered three times with 200 mL tap water and left to drain for 30 min. Each pot was then elevated over a saucer using a polyvinyl chloride ring. Subsequently, 40 mL of tap water was poured uniformly over the surface of each pot, avoiding the container edge. After 5 min, leachate collected in the saucer was transferred into a 50-mL conical tube. The tubes were capped and brought to the laboratory for pH measurement.

Results and Discussion

Substrate physical properties. Particle size distribution of the sphagnum peat and

Table 1. Percent particle size distribution of sphagnum peatmoss and three pine bark (*Pinus taeda*) products screened differently for various horticultural uses.

	Peatmoss	Fine bark	Med. bark	Coarse bark	LSD _{0.05} ^a
Sieve size (mm)	----- (%) -----				
Pan	1.8	2.3	2.7	1.0	0.4
0.11	4.5	4.1	3.3	1.3	0.3
0.18	5.9	4.1	3.5	1.4	0.5
0.25	8.6	7.0	4.9	2.5	0.8
0.35	8.7	9.2	5.9	3.6	1.0
0.50	10.9	13.7	8.3	6.1	1.4
0.71	7.4	13.5	8.1	5.9	0.6
1.00	6.4	15.9	9.1	7.0	1.1
1.40	7.8	17.1	11.4	8.9	0.7
2.00	7.3	9.3	11.5	9.5	0.8
2.80	11.0	3.6	15.4	14.2	1.8
4.00	12.2	0.3	12.6	19.9	2.9
6.30	7.5	0.0	3.2	18.7	2.0
Fine ^b	29.5	26.6	20.3	9.7	2.5
Medium	39.8	69.5	48.5	37.5	3.1
Coarse	30.7	3.9	31.2	52.8	5.3

^aFisher's least significant difference among values within the same row.

^bFine particles are those in sieves $<0.50 \text{ mm}$, medium particles are 0.50 to 2.00 mm , and coarse particles are $>2.00 \text{ mm}$.

Fig. 1. Solution pH of peat and bark samples exposed to acid or base solutions from 0 to $50 \text{ meq}\cdot\text{L}^{-1}$. For graphing purposes, acid solutions are represented by decreasingly negative values in $\text{meq}\cdot\text{L}^{-1}$. The experiment was repeated, with panels A and B representing the first and second iterations, respectively.

three pine bark substrates differed (Table 1). Sphagnum peat had a greater percentage of fine particles (>0.5 mm) than all pine bark textures, but a similar percentage of medium (0.5 to 2.0 mm) and coarse particles (>2.0 mm) as the coarse- and medium-textured pine barks, respectively. Among the three bark textures, the percent of fine and medium particles decreased whereas the percent of coarse particles increased as bark texture shifted from fine to coarse. Jackson et al. (2010) observed a similar phenomenon with pine tree substrates processed with a hammermill equipped with varying screen sizes. There were significant differences within each of the sieve sizes between the three bark textures; however, the largest differences occurred with the larger sieve sizes (Table 1). This is somewhat expected because these three bark textures were produced by a single company using varying combinations of screens to remove coarse particles.

The physical properties of the four substrates differed (Table 2). Peat and fine bark had similar AS, CC, and TP; however, D_b of the fine or medium bark was more than twice that of the peat. Among the three bark textures, AS was greatest for the coarse bark, and CC decreased from fine to coarse textures. Because TP is calculated as the sum of AS and CC, it tends to stay consistent across substrates with different particle sizes as the inverse relationship between AS and CC leads to relatively constant TP. Altland

et al. (2018) previously showed that among pine bark sources with varying textures and wide-ranging AS and CC, the inverse relationship between the two variables resulted in similar TP across bark sources.

pH buffering of substrate type. Sphagnum peat and the three pine bark textures had different pH buffering curves (Fig. 1). In the first iteration of the experiment, the pH of sphagnum peat and fine, medium, and coarse pine barks with pure water (0 meq·L⁻¹ acid or base) were 3.76, 3.80, 4.23, and 4.17, respectively (data not shown). Minimum solution pH was 2.36. Sphagnum peat pH was reduced to 2.72, but fine and medium bark pH was almost a half unit higher at 3.22 and 3.26, respectively, as depicted by the fitted parameter y_0 representing the asymptotic minimum of the curve (Table 3). It appears that sphagnum peat had the least buffering capacity in acidic solutions as the pH of sphagnum peat was pulled closer to the solution pH. The total reduction in pH of peat and fine, medium, and coarse bark in the most acidic solution was 1.06, 0.55, 0.96, and 0.99 pH units, respectively. From the standpoint of pH reduction in the strongest acid solution compared with that in pure water, fine bark was reduced the least while sphagnum peat and the medium and coarse bark were reduced by ≈ 1 pH unit. However, because pH is a logarithmic value, the reduction of pH should be assessed on the change in acidity. The decrease in sphagnum peat pH from 3.76 to 2.72 required a greater change in acidity ($\Delta 0.0018 \text{ M H}^+$) than a

similar reduction of pH in medium bark where pH was reduced from 4.23 to 3.28 ($\Delta 0.0004 \text{ M H}^+$). Therefore, peat had the least buffering capacity in acidic solutions. Poor acid pH buffering of sphagnum peat might in part explain the sudden pH decline observed with geranium (*Pelargonium xhortorum* L.H. Bailey) (Taylor et al., 2008), which are grown primarily in sphagnum peat-based substrates. Sphagnum peat had greater pH buffering against basic solutions than the medium or coarse bark in the first iteration of the experiment, although fine bark had the greatest buffering capacity against bases, with a maximum pH of 5.65 relative to the solution pH of 12.47 (Fig. 1). The change in molar OH⁻ concentration followed the same trend as pH. Fine bark increased the least ($4.42 \times 10^{-9} \text{ M OH}^-$), followed by sphagnum peat (increased $1.24 \times 10^{-8} \text{ M OH}^-$), and the medium and coarse barks (increased 1.70 and $1.11 \times 10^{-7} \text{ M OH}^-$, respectively). The fitted parameter b of the log-logistic function could be indicative of pH buffering. The lower the value, the steeper the transition is from low pH values (y_0) to high pH values ($y_0 + a$). By extension, the steeper the transition, the fewer meq of acid or base are needed to change pH, indicating lower pH buffering. Sphagnum peat had the lowest values for parameter b in the first iteration of the experiment. In the second iteration of the experiment, sphagnum peat again exhibited lower acid pH buffering as well as greater base pH buffering than all pine bark textures (Fig. 1). The three pine bark textures had similar pH buffering when exposed to acidic solutions, whereas the coarse bark displayed lower pH buffering than the other two bark textures when exposed to basic solutions. The $y_0 + a$ parameters for coarse bark in the second iteration of the experiment (Table 3) suggest maximum pH would be 19.99. This unreasonable value is likely due to how the data were fit with the log-logistic function to this particular data set. The pH response of this substrate (Fig. 1) over the range of acid and base solutions evaluated resembles a more quadratic polynomial response instead of a sigmoidal response.

pH buffering by particle size fraction. Sphagnum peat pH was 3.41, 3.51, and 3.38 for the 0.18-, 0.71-, and 2.8-mm particle size fractions, respectively, in pure water with 0 meq·L⁻¹ acid or base (Fig. 2). Pine bark pH was 4.17, 4.13, and 4.11 for the same three particle size fractions, respectively, in pure water. Sphagnum peat pH decreased more (y_0) than pine bark when adding a strong acid solution to the fine particles (0.18 mm), but they both decreased a similar amount in the medium and coarse particles (0.72 and 2.8 mm, respectively) (Table 4). However, sphagnum peat molar H⁺ concentration was reduced greater than pine bark with each particle size class [0.018 vs. 0.001 (0.18 mm), 0.016 vs. 0.004 (0.71 mm), and 0.019 vs. 0.004 (2.8 mm) M H⁺ for peat vs. pine bark, respectively]. This corroborates the results observed in the first experiment. Elliott (1996) also showed that an acidic

Table 2. Physical properties of sphagnum peatmoss and several pine (*Pinus taeda*) bark products screened differently for various horticultural uses.

Substrate type	Air space ^z	Container capacity	Total porosity	Bulk density (g.cm ⁻³)
	----- (%) -----			
Peat	16.1	62.6	78.8	0.084
Fine bark	17.1	62.4	79.5	0.176
Medium bark	19.4	48.2	67.6	0.179
Coarse bark	35.5	39.7	75.2	0.158
LSD _{0.05} ^y	6.1	2.8	6.0	0.017

^zAir space is percent volume of 7.6 × 7.6-cm core filled with air after saturation and drainage. Container capacity is percent volume of the same core filled with water after drainage. Total porosity is calculated as the sum of air space and container capacity.

^yFisher's least significant difference among values within the same row.

Table 3. Estimated parameters for log-logistic curves that describe the buffering of pine bark against acidic and basic solutions ranging from 50 meq·L⁻¹ acidity to 50 meq·L⁻¹ basicity (Fig. 1).

Substrate	y_0^z	$y_0 + a$	b	x_0	r^2
(meq·L ⁻¹)					
Expt. 1					
Peat	2.72	6.10	14.19	11.93	0.9969
Fine bark	3.22	5.65	19.85	19.89	0.9950
Medium bark	3.26	7.23	18.13	18.03	0.9917
Coarse bark	3.09	7.04	19.02	15.83	0.9971
Solution	2.36	12.47	3.59	-1.90	0.9988
Expt. 2					
Peat	2.42	6.17	23.41	15.47	0.9959
Fine bark	3.41	5.66	13.58	8.98	0.9950
Medium bark	2.82	8.08	39.72	34.23	0.9990
Coarse bark	2.49	19.99	42.15	84.95	0.9943
Solution	2.24	12.34	3.59	-1.90	0.9988

^zParameters estimated for the log-logistic function $\text{pH} = y_0 + a / \{1 + \exp[-(x - x_0)/b]\}$, where y_0 represents the lowest pH value of the substrate incurred by exposure to acidic solution, $y_0 + a$ represents the maximum pH value, b is a scaling factor, and x_0 is the acid/base concentration (meq·L⁻¹) at which the curve changes from convex to concave. The parameter r^2 is the coefficient of determination for the model.

Fig. 2. Solution pH in peat or bark samples, sifted to 0.18-, 0.71-, or 2.8-mm particles and saturated in 0 to 50 meq·L⁻¹ of an acid or base solution. For graphing purposes, acid solutions are represented by decreasingly negative values in meq·L⁻¹.

fertilizer solution reduced pH in a sphagnum peat substrate (2 sphagnum peat: 1 vermiculite) greater than a bark substrate (2 sphagnum peat: 3 pine bark: 1 vermiculite). Both pH and molar OH⁻ concentration in our study increased more in pine bark compared with sphagnum peat in all three particle size fractions, especially in the 0.71-mm particle size, in which pine bark pH was more than 2 units higher and molar OH⁻ concentration was more than two orders of magnitude greater than sphagnum peat. Jackson et al. (2010) likewise showed that sphagnum peat was more resistant to change in pH from limestone addition compared with pine tree substrates that included pine bark and wood. Similar to the first experiment, the b parameter was lower for sphagnum peat in all three particle size fractions compared with pine bark, indicating a steeper transition between minimum and maximum pH and thus less buffering capacity at low to moderate (<20 meq·L⁻¹) acid and base additions.

Greenhouse experiment. Irrigation water treatments used in the experiment had wide-ranging pH and alkalinity to simulate how acidic and basic solutions affect substrate pH under typical irrigation practices (Table 5). At the initiation of the experiment, sphagnum peat, fine bark, and coarse bark had pH of 3.41, 5.37, and 4.81, respectively (Table 6). The pH of all three substrates remained stable over the 8-week experimental period when

Table 4. Estimated parameters for log-logistic curves that describe the buffering of peatmoss or pine bark, each screened to one of three different particle sizes, against acidic and basic solutions ranging from 50 meq·L⁻¹ acidity to 50 meq·L⁻¹ basicity (Fig. 2).

Particle size	Substrate	y_0^z	$y_0 + a$	b	x_0	r^2
0.18 mm	Peat	1.73	5.55	13.66	3.35	0.9982
	Bark	2.84	6.40	18.99	9.66	0.9960
0.71 mm	Peat	1.77	6.02	10.44	3.85	0.9957
	Bark	2.36	8.11	27.48	22.20	0.9987
2.8 mm	Peat	1.69	5.71	14.84	4.75	0.9960
	Bark	2.44	7.30	21.56	13.84	0.9987
	Solution	1.58	12.79	2.91	2.56	0.9995

^zParameters estimated for the log-logistic function $pH = y_0 + a / \{1 + \exp[-(x - x_0)/b]\}$, where y_0 represents the lowest pH value of the substrate incurred by exposure to acidic solution, $y_0 + a$ represents the maximum pH value, b is a scaling factor, and x_0 is the acid/base concentration (meq·L⁻¹) at which the curve changes from convex to concave. The parameter r^2 is the coefficient of determination for the model.

Table 5. Treatment pH and alkalinity created by adding HCl or NaOH to tap water or an acidic water soluble fertilizer (Fert.), H₂SO₄, or KHCO₃ to tap water.

Acid/base	Fertilizer	pH	Alkalinity (mg·L ⁻¹ CaCO ₃)
Tap water control	—	8.72 ± 0.36	47.8 ± 4.5
HCl	—	1.96 ± 0.10	0.0 ± 0.0
NaOH	—	12.46 ± 0.37	375.0 ± 80.1
Tap water	Fert.	7.27 ± 0.29	48.6 ± 6.0
H ₂ SO ₄	Fert.	2.05 ± 0.10	0.0 ± 0.0
KHCO ₃	Fert.	8.36 ± 0.38	519.4 ± 54.2

Table 6. Substrate pH in peatmoss, fine pine bark, and coarse pine bark after irrigation with tap water amended with either 10 meq·L⁻¹ of HCl, NaOH, H₂SO₄, or KHCO₃ and with or without 20–10–20 water soluble fertilizer (Fert., 20N–4.4P–16.6K–0.15Mg–0.02B–0.01Cu–0.1Fe–0.05Mn–0.01Mo–0.05Zn). Substrate pH was recorded before irrigation (week 0) and at 4 and 8 weeks after initiating irrigation regime.

Substrate	Acid/base	Fertilizer	0 wk	4 wk	8 wk
Peatmoss	Water control		3.41	3.42	3.45
	HCl			2.35	2.12
	NaOH			3.47	3.71
	Water	Fert.		3.24	3.28
	H ₂ SO ₄	Fert.		2.90	2.28
	KHCO ₃	Fert.		3.38	3.67
Fine bark	Water control		5.37	5.04	5.15
	HCl			4.35	3.35
	NaOH			6.01	6.67
	Water	Fert.		5.38	5.31
	H ₂ SO ₄	Fert.		4.96	3.93
	KHCO ₃	Fert.		6.52	6.68
Coarse bark	Water control		4.81	4.82	4.87
	HCl			3.65	2.58
	NaOH			6.00	6.68
	Water	Fert.		5.04	4.73
	H ₂ SO ₄	Fert.		4.42	3.00
	KHCO ₃	Fert.		6.73	6.90
LSD _{0.05} ^z			0.57	0.30	0.28

^zLeast significant difference among values within the same row.

irrigated with greenhouse tap water (±0.3 units). The pH of sphagnum peat exposed to HCl decreased by 1.3 units from the initial measurement after 8 weeks. The pH of fine and coarse pine bark decreased 2.0 and 2.2 pH units, respectively, after 8 weeks. However, the change in molar H⁺ concentration of sphagnum peat after 8 weeks was greater (0.0072 M H⁺) than the change for the fine and medium pine bark (only 0.0004 and 0.0026 M H⁺, respectively) due to the logarithmic nature of pH and the lower starting pH of the sphagnum peat substrate. Therefore, similar to the laboratory studies, sphagnum peat had a lower buffering capacity against acidic, low

alkalinity solutions than pine bark. When irrigated with a basic, high-alkalinity solution using NaOH, sphagnum peat pH increased by 1.3 units after 8 weeks, while fine and coarse bark increased 1.3 and 1.9 units, respectively. These data corroborate the results from our laboratory studies that pine bark is less buffered to changes in pH when irrigated with basic solutions.

Substrates were also irrigated with a standard greenhouse water-soluble fertilizer (acidic with a calcium carbonate equivalency of 200 kg per metric ton) and more traditional acidic and basic materials used during crop production (H₂SO₄ and KHCO₃). Similar to

the water control treatment, the pH of substrates exposed to the water-soluble fertilizer were unaffected (Table 6). Although pH of the fertilizer solution was 1.5 units lower than the control water (7.27 vs. 8.72), both sources had similar alkalinity (Table 5). Irrigation water alkalinity has been shown to be more influential on substrate pH than irrigation water pH (Ramirez and Altland, 2018). Irrigating with fertilizer and H₂SO₄ decreased sphagnum peat pH 0.5 and 1.1 units after 4 and 8 weeks, respectively. It decreased fine and coarse bark by 1.4 and 1.8 pH units, respectively, after 8 weeks. Despite a greater decrease in pH in the two bark substrates compared with sphagnum peat, the change in molar H⁺ concentration was less. Irrigating with fertilizer and KHCO₃ increased pH of sphagnum peat pH by 0.3 units, fine bark by 1.3 units, and coarse bark by 2.1 units after 8 weeks. Similar to our laboratory experiments, sphagnum peat had a lower buffering capacity than pine bark against changes in acidity, whereas pine bark had a lower buffering capacity than sphagnum peat to changes in basicity.

There are several practical implications of this research. First, particle size appears to affect pH buffering of some organic substrates but not others, which may be due to their cation exchange capacity (CEC). CEC and pH buffering in organic matter are related, as both mechanisms are moderated by dissociation of carboxyl groups that act as sinks for H⁺ and OH⁻ (Curtin and Rostad, 1997; Parfitt et al., 1995). CEC in pine bark has been shown to increase with decreasing particle size over the range of 0.25 to 4 mm (Altland et al., 2014). The fine, medium, and coarse pine bark used in this study had different particle size distributions (Table 1). These three substrates, as well as bark screened to different particle sizes between 0.18 and 2.8 mm, had demonstrable differences in pH buffering in basic solutions (Tables 3 and 4). In contrast, Altland et al. (2014) showed that CEC of sphagnum peat changed little with particle size over the range of 0.25 to 4 mm, and likewise we had only minor differences in pH buffering in acidic and basic solutions using sphagnum peat particles screened to sizes ranging from 0.18 to 2.8 mm (Table 4).

Second, although not an objective of the experiment, the greenhouse study further illustrates how irrigation water alkalinity has a greater impact on substrate pH than irrigation water pH. In a 17-week container study evaluating the effects of irrigation alkalinity from different water and fertilizer sources, Argo and Biernbaum (1996) also showed that substrate pH was similar when treated with irrigation water having similar alkalinity. Although irrigation water pH and alkalinity can be related, a survey of Ohio groundwater samples showed little correlation between the two variables ($R = -0.16726$,

$P = 0.0006$, $R^2 = 0.027$, $n = 416$) (Anonymous, 2019). Therefore, knowing irrigation water pH alone is not adequate for understanding how substrate pH might change over time. Alkalinity is not easily measured by growers, but it is commonly included in most commercial and university water quality laboratory analyses.

Third, data from these experiments demonstrate that a singular value cannot be used to represent pH buffering of sphagnum peat and pine bark. Resistance to pH change of both substrates differed with exposure to acidic and basic solutions. In all cases, sphagnum peat was more susceptible to acidic changes but more resistant to basic changes compared with pine bark. The parameter b of the log-logistic curve was suggested herein to be representative of buffering capacity because this parameter indicates the steepness of the change between the minimum and maximum horizontal asymptotes of the curve. However, based on our findings that individual substrate components and particle sizes can differ in their buffering capacity between acidic and basic solutions, a singular value such as parameter b could be misleading.

Lastly, because sphagnum peat and pine bark are more buffered against changes in basic and acidic solutions, respectively, they might be used strategically in substrate blends to counter prevailing pH drivers. For example, growers might use a higher rate of sphagnum peat in substrates where high water alkalinity causes problems with pH increasing over time. In contrast, growers might use a higher rate of pine bark in situations where acidic fertilizers and low irrigation water alkalinity result in reduced substrate pH over time.

In summary, the objective of this research was to compare the pH buffering capacity of pine bark and its particle size fractions to sphagnum peat. We concluded that a singular value cannot accurately describe pH buffering against both acidic and basic drivers. Sphagnum peat used in this experiment was less buffered against acidic solutions than pine bark, but more buffered against basic solutions. The pH buffering of basic solutions in pine bark decreased with increasing particle size. Further research is needed to determine if the results of these particular batches of sphagnum peat and pine bark can be generalized across all sphagnum peats and barks.

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