The Pour-through Procedure Preferentially Extracts Substrate Solution from the Bottom of the Container in Conventional and Stratified Substrates

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Abstract. Due to the widespread use of the pour-through extraction procedure in horticultural production and research, the objective of this study was to determine if the method is biased by preferentially extracting substrate solution near the bottom of the container in both conventionally filled containers as well as intentionally stratified containers. Eight treatments were created using 2.5-L, 17.5-cm tall plastic nursery containers. The first four treatments were created by layering a conventional pine bark substrate (CONV) that was either amended (+A) or nonamended (−A) with fertilizer and lime with the following layers: amended substrate throughout the entire container profile (+A/+A); amended substrate in the top half (top 8.5 cm) over nonamended substrate in the bottom half of the container profile (+A/−A); nonamended substrate in the top half over amended substrate in the bottom half (−A/+A); and nonamended substrate throughout the profile (−A/−A). An additional four treatments were created by intentionally stratifying (STRAT) a fine pine bark substrate (FINE) over a coarse pine bark substrate (CRSE) with the same amendment combinations of +A or −A. On 0 and 42 d after potting, substrate pH and electrical conductivity (EC) were determined on samples collected by the pour-through procedure and 1:1 water extracts of the top and bottom layers in the container. At 42 d after potting, nutrient ions (NO_3^-, PO_4^{2-}, K, Ca, Mg, and SO_4^{2-}) were also measured in both pour-through and 1:1 water extracts of the top and bottom layers. At both dates and in both CONV and STRAT containers, pour-through substrate pH and EC more closely reflected those measurements in the bottom half of the container as determined by the 1:1 water extract. At 42 d after potting, nutrient ions determined by the pour-through procedure were more highly correlated to the 1:1 water extracts from the bottom half of the container compared with the top half of the container in both CONV and STRAT substrates. Evidence herein demonstrates that the pour-through procedure is more reflective of the lower half of the container than the upper half for both CONV and stratified substrates.

The pour-through procedure is widely used in commercial horticulture production and research to monitor the fertility of container-grown plants and to infer mineral nutrient availability (Altland 2021). The procedure involves the extraction of an aliquot of substrate solution from the bottom of the container by pouring water over the surface of a containerized substrate after being brought to container capacity (CC) or maximum water holding capacity (Wright 1986). The collected aliquot or sample, resulting from displaced leachate, can then be analyzed for pH, EC, dissolved mineral ions, and other chemical properties. The four primary benefits of the pour-through procedure are that it is 1) nondestructive, it can be 2) low cost, needing only water and electrochemical meter(s) to measure pH and EC, 3) used to measure substrate electrochemical properties rapidly and repeatedly, and it is 4) simple and robust enough to have become a widespread tool used in both commercial production and horticultural crop research. Several factors affect the results from the pour-through procedure, including displacement solution volume (Nuñez and Osborne 2014; Yao et al.

2008), subsequent extraction volume (Yeager et al. 1983), container size (Torres et al. 2010), timing of displacement solution after saturation (Cavins et al. 2005), and substrate type (Niemiera et al. 1994).

Handreck (1994) first demonstrated the pour-through method provides pH and EC values representative of the bottom strata of a container when filled with peat and composted eucalypt sawdust mixtures. He collected a pour-through sample, composed of the first 6 mL of leached solution (compared with the standard protocol of collecting at least a 50-mL sample), to saturated media extracts (SME) of substrate fractions representing four equal sections of the vertical container profile. Without statistics, Handreck (1994) claimed pH of the pour-through sample was more closely related to SME pH in the bottom strata of the container than the bulk substrate SME representing the entire vertical container profile. He goes on to conclude that containers should be checked for the absence of large vertical variation in pH or EC before pour-through extracts can be considered reliable.

Substrate stratification occurs unintentionally in virtually all container systems. Containers in commercial production of floriculture and nursery crops are traditionally filled uniformly with a single mixed substrate. Following every irrigation event, opposing forces from gravitational potential gradient and capillary water retention (i.e., matric potential) create a zone of saturation called the perched water table at the container bottom (Spomer 1990), with decreasing volumetric water content with increasing vertical container height (Owen and Altland 2008). This volumetric water gradient affects chemical and biological properties including decomposition processes (Walse et al. 1998), mineral nutrient release from controlled release fertilizers (CRFs) (Du et al. 2006), and gas emissions from the substrate (Marble et al. 2012).

More importantly, pH and EC (the primary parameters measured from pour-through extracts) form an electrochemical gradient within the vertical profile of the container. Wada et al. (2006) showed decreasing substrate pH in containers from the surface to the container bottom and attributed the higher pH near the substrate surface to alkalinity of surface applied irrigation water having greater effect on the substrate surface than lower in the container. Jeong et al. (2012) reported the opposite trend, with pH increasing from the top to the bottom, whereas EC decreased. They (Jeong et al. 2012) attributed the gradient to fertilizer solution being applied to the substrate surface causing acidification reactions near the top of the container and less so lower in the container profile. Others (Handreck 1994; Ku and Hershey 1991) reported results similar to Jeong et al. (2012) and further speculated that accumulation and nitrification of ammonium near the surface from application of water-soluble fertilizers are responsible for reduced pH near the top of the container. Molitor (1990) similarly showed reduced pH in the lower portion of the container when fertilizer solution was applied via

sub-irrigation. Regardless of the vertical direction of pH and EC gradients, the pour-through procedure could provide misleading results if the lower portion of the vertical profile is preferentially represented in a pour-through sample as suggested by Handreck (1994).

Substrate stratification can also be an intentional construct within the container. Stratifying substrates within the container has recently emerged as a new concept in container management. Intentional substrate stratification refers to layering more than one substrate type or fertilizer amendment in strata within the vertical profile of the container. Stratifying substrates has been shown to improve substrate hydrology and water use efficiency (Criscione et al. 2022a), reduce fertilizer rates necessary for optimum crop yield (Fields et al. 2021), reduce leachate nutrient loads (Hoskins et al. 2014a), and specifically reduce phosphorus leaching (Shreckhise and Altland 2020, 2021). Using the pour-through procedure on intentionally stratified containers could also cause erroneous results if the bottom stratum is preferentially represented in the sample, especially if fertilizer placement is part of the intentional stratification construct.

Due to the widespread use of the pour-through procedure, the objective of this research was to determine if the pour-through procedure is biased by preferentially sampling substrate solution near the bottom of the container in both uniformly filled containers as well as intentionally stratified containers.

Materials and Methods

Substrate treatment preparation

A CONV, stabilized (i.e., aged) pine (*Pinus taeda* L.) bark (PM2; Pacific Organics, Inc. Henderson, NC) that had previously passed through a 12.5-mm-mesh sieve was further separated using a 6.3-mm-mesh, 41 × 61-cm screen tray, vibrated at an angle of 10° with 8.3 oscillations/s using a continuous-flow screen shaker (Gilson Company, Inc., Lewis Center, OH, USA). Bark passing through the screen was classified as fine (FINE), whereas bark unable to pass through the screen was classified coarse (CRSE). Each substrate type, CONV, FINE, and CRSE, was placed into 68-L containers with drain holes, watered, and placed in an open-air environment to equilibrate for 30 d with respect to moisture content. Each equilibrated, moistened pine bark type was then thoroughly mixed to ensure homogeneity before being analyzed for physical properties and particle size distribution (described later) and further division into individual 70-L batches.

Separate 70-L batches of substrate either received no amendments (−A) or were amended with 4.7 and 9.5 kg·m^{-3} dolomitic lime and CRF, respectively, (+A). To amend the substrate homogeneously, 336 g pulverized dolomitic lime (95.0% CaCO$_3$ equivalent, 21.6% calcium, 10.0% magnesium; Soil Doctor, Atlanta, GA, USA) and 672 g (1.5x label high rate) of a 18N–2.2P–6.6K 3 to 4 mo (21 °C) CRF with minors (6.3% ammoniacal nitrogen, 5.4% nitrate nitrogen, 6.3% urea nitrogen, 5.4% combined

sulfur, and 1.3% magnesium; ICL Specialty Fertilizers - Americas, Summerville, SC, USA) was incorporated into 70 L of pine bark by hand mixing. Each substrate was filled in clean 70-L containers, placed in a glass greenhouse maintained at 21 °C, and watered as needed to remain moist and minimize leaching for ~30 d to ensure lime and CRF were activated.

Static physical properties of each substrate were determined using a packed 347-cm^3 aluminum core (7.6 cm tall × 7.6 cm i.d.) according to methods described by Fonteno and Bilderback (1993). There were six replications for each substrate. Aluminum cores were attached to North Carolina State University Porometers™ (Horticultural Substrates Laboratory, North Carolina State University, Raleigh, NC, USA), 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 CC. Total porosity (TP) was calculated as the sum of AS and CC (Table 1). Bulk density (D$_b$) was determined using the oven-dried (110 °C) substrate. Particle size distribution of each sample was determined using ~100 cm^3 of oven-dried substrate (60 °C) and passing it through 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 sieves. Particles ≤ 0.11 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). Coarse, medium, and fine texture (Table 1) were determined by calculating the sum of the respective screens within a given particle size range.

Potting, maintenance, and final data collection

Potting. Each batch of moistened substrate was again mixed to ensure homogeneity before being transferred to 2.5-L, 17.5-cm-tall injection molded nursery containers (#1, NS300; Nursery Supplies Inc., Chambersburg, PA, USA). Eight treatments were created. The first four treatments were created by layering the CONV amended (+A) or nonamended (−A) pine bark (Fig. 1), including 1) amended substrate throughout the entire container profile (+A/+A); 2) amended substrate in the top half (top 8.5 cm) over nonamended substrate in the bottom half of the container profile (+A/−A); 3) nonamended substrate in the top half over amended substrate in the bottom half (−A/+A);

and 4) nonamended substrate throughout the profile (−A/−A). An additional four treatments were created by layering FINE over CRSE substrate with the same combinations of +A or −A (Fig. 1). There were 10 single pot replications per treatment arranged on a greenhouse bench in a completely randomized design. Additional containers were maintained to determine evaporative water loss by weighing dry vs. saturated containers. Remaining substrate of all types, amended or nonamended, were placed in sealable bags and stored in a refrigerator until a 1:1 extract analysis was performed.

All containers were placed on a greenhouse bench. The extra containers described previously were saturated thoroughly and weighed to determine container weight at saturation. Each additional container was brought to the point of saturation by determining the volume of water needed to reach saturation and hand watering slowly and carefully to saturate the containers with minimal leaching.

One day after potting and saturating, six of 12 replications were subjected to the pour-through procedure as described in the following text. All remaining containers were hand watered with deionized water about every 5 days based on evaporative loss as calculated by weighing the extra pots between irrigation events to nearly eliminate leaching.

At 42 d after initial potting and saturation, the final six replications were subjected to the pour-through procedure. A 250-cm^3 aliquot of the top and bottom halves of each container was collected using a metal spoon and placing in separate Ziplock bags. Bags were placed in a refrigerator until 1:1 water extraction could be conducted.

Substrate pore-water extraction and analysis

Pour-through extract. Extractions (Wright 1986) were performed 60 min after irrigation of containers. Containers were elevated 2.5 cm above a shallow plastic saucer using a PVC ring to allow for ease of colleting an uncontaminated extractant. Deionized water (100 mL) was applied evenly to the substrate surface. After 20 min of drainage, ~50 to 75 mL extractant was collected from each container for pH, EC, and pore-water analysis (see the following).

Water extract. To each Ziplock bag with a 250-cm^3 aliquot of substrate, 250 mL deionized water was added before thoroughly being mixed to ensure saturation and equilibration for 1 h. At

Table 1. Static physical properties and particle size range of three stabilized (i.e., aged) pine (*Pinus taeda* L.) bark substrates prepared to have different textures: conventional (CONV), coarse (CRSE), and fine (FINE).

Substrate	Air space	Container capacity	Total porosity	Bulk density
	% by vol.			g·cm^{-3}
CRSE[i]	48.8 a[ii]	31.1 c	79.9	0.116 c
FINE[iii]	32.1 b	53.4 a	85.6	0.150 a
CONV[iv]	38.9 b	44.6 b	83.5	0.137 b
P value	0.0021	<0.0001	0.1442	<0.0001

[i] Coarse fraction of conventional bark after passing over a 6.3 mm screen.
[ii] Means within a column with similar letters are not significantly different.
[iii] Fine fraction of a conventional bark after passing through a 6.3 mm screen.
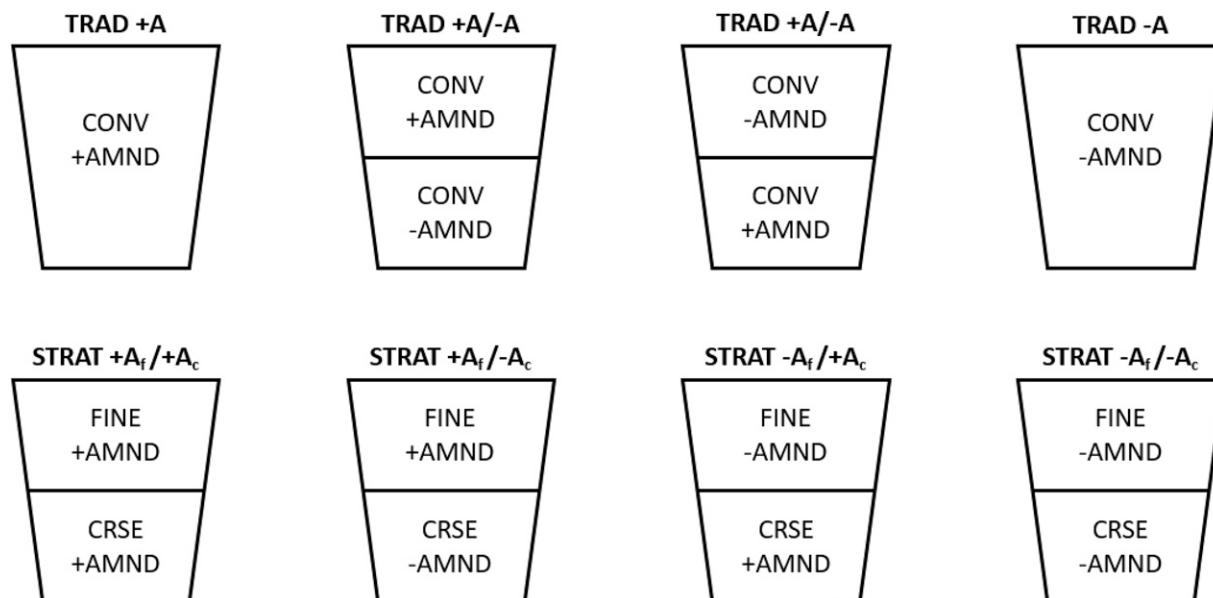[iv] Conventional aged pine bark screened to be <12.5 mm.

Fig. 1. An illustration of treatment design using a conventional (CONV), stabilized (i.e., aged) pine (*Pinus taeda* L.) bark that had previously passed through a 12.5-mm-mesh sieve or further separated using a 6.3-mm-mesh using a continuous-flow screen shaker. Bark passing through the screen was classified as "fine" (FINE), whereas bark unable to pass through the screen was classified "coarse" (CRSE). Substates either received no amendments (−A) or were amended (+A, +AMND) with 4.7 and 9.5 kg·m⁻³ pulverized dolomitic lime and an 18N–2.2P–6.6K 3- to 4-mo (21 °C) controlled release fertilizer (CRF) with minors. Substrate was then used to fill the containers traditionally (TRAD), in which the CONV substrate was used to fill the entire container or in a stratified (STRAT) construct, with FINE atop of CRSE substrate.

the end of 1 h, pH and EC was recorded directly in the slurry before filtration with 10 cm glass fiber filters (Catalog No. 09-804-110A; Fisher Scientific, Hampton, NH, USA) via a glass vacuum flask and polypropylene Buchner funnel. Filters retained particles <3 μm. Filtrate was saved for pore-water analysis.

Pore-water analysis. Pore-water extracts were separated to determine pH and EC or nutrient ions (NO_3^-, PO_4^{2-}, K, Ca, Mg, and SO_4^{2-}). An ∼5- to 15-mL aliquot of the nonfiltered samples was analyzed for pH and EC using a benchtop meter (S470 SevenExcellence; Mettler Toledo, Columbus, OH, USA) with a pH electrode (Expert Pro-ISM; Mettler Toledo) and EC was analyzed with a conductivity meter (S230 SevenCompact; Mettler Toledo) and electrode (741-ISM) in a 15-mL conical tube. A 7-mL aliquot of each extract was placed in a 10-mL syringe (Henke-Ject; Heke Sass Wolf of America, Dudley, MA, USA) and filtered [0.45-μm polyethersulfone (PES) membrane, 25-mm-diameter syringe filter (Laboratory Safety Supply; Grainger, Lake Forest, IL, USA)] before cation and anion concentration analysis via ion chromatography (IC) system (Dionex ICS-6000; Thermo Scientific, Madison, WI, USA). The IC system used 2·250-mm (i.d.·length) anion- and cation exchange columns (AS19, CS12A, respectively, Thermo Scientific) at 35 °C and an autosampler (Autoselect Polyvial 074228; Thermo Scientific).

Data analysis and statistics

Physical properties data were subjected to analysis of variance (ANOVA) and means were separated with Fisher's protected least significant difference. Mean substrate pH, EC, and nutrients from either the pour-through procedure or 1:1 water extracts were calculated with 95% confidence intervals (CIs) and subjected to ANOVA and means separation. Correlation coefficients were calculated between substrate pH, EC, and nutrients. All analyses were conducted with a statistical software package (SAS version 9.4; SAS Institute, Cary, NC, USA).

Results and Discussion

Physical properties. The AS of CONV substrates was nearly the midpoint between that of FINE and CRSE (Table 1), likely because the latter two substrates were made by screening CONV into two separate fractions. Fields et al. (2021) reported a similar trend with pine bark that was also separated with a 6.3-mm screen. As expected, the CRSE had greater AS than the FINE. A similar result occurred with CC where CONV was nearly midpoint of the two screened substrates; however, in this case FINE had greater water retention than CRSE. All three substrates had similar TP, calculated as the sum of AS and CC. TP is often similar across substrates differing only in particle size distribution due to the inverse relationship between AS and CC for many soilless substrates (Altland et al. 2018). Similar to AS and CC, bulk density of the CONV substrate was intermediary between the CRSE and FINE substrates. Other research has shown that bulk density can often be calculated as the weighted mean of two substrates (Gabriel et al. 2009; Pokorny et al. 1986).

Conventional substrate at potting. Substrate pore-water pH determined by the pour-through method in containers when both the top and bottom strata were nonamended was 4.4, compared with 4.6 for the same substrate measured when using the 1:1 water extract (Table 2). Although the two values were not compared statistically, the 95% CIs about the means overlapped. Likewise, pore-water pH of containers filled completely with pine bark amended with dolomitic lime was 6.6 as determined by the pour-through procedure, and 6.8 with 1:1 water extract (Table 2), with overlapping 95% CIs.

When the bottom half of the containers were filled with nonamended substrate, the pH determined with the pour-through was 4.1 and 4.4 when the top portion of the bark was amended and nonamended, respectively (Table 2). Containers with the top half of the substrate amended with a high dolomitic lime rate showed no evidence of elevated pH, and even had slightly depressed pH compared with containers in which the top half was nonamended. This suggests that the pore-water extracted by the pour-through method was solely from the bottom portion of the container. Likewise, when the bottom half of the container was amended with a high rate of dolomitic lime, pore-water pH extracted using the pour-through was 6.5 or 6.6 if the top portion of the container was amended or not, respectively. Again, the pour-through on these containers reflected the pH conditions of only the bottom portion of the container.

EC determined by pour-through extracts of containers filled completely with nonamended substrate was 209 μS·cm⁻¹, compared with just 56.1 μS·cm⁻¹ for the same treatment when using the 1:1 water extract (Table 2). This highlights one important difference in these two

Table 2. Substrate pore-water pH, electrical conductivity (EC), n nitrate (NO_3^-), ammonium (NH_4^+), dissolved inorganic nitrogen (DIN; $NH_4 + NO_3 + NO_2$), phosphate phosphorus (PO_4^--P), and potassium (K) concentration as measured with the pour-through procedure on containers that were filled either halfway or fully with either a traditional pine bark substrate (<12.6 mm) amended with pulverized dolomitic lime and 18N–2.2P–6.6K 3- to 4-mo controlled release fertilizer or a without amendment. Separate samples of the amended or nonamended bark were also analyzed for the same parameters using the 1:1 water extract procedure. Data are presented as the mean ± 95% confidence interval (n = 6). LSD = least significant difference.

Location	Conventional substrate description	pH	EC	NO_3^-	NH_4^+	DIN	PO_4^--P	K
		Pour-through extract of containerized substrate immediately following potting						
Top	Not amended	4.4 ± 0.1	209 ± 22	2.9 ± 2.7	0.0 ± 0.0	0.6 ± 0.6	1.7 ± 0.7	47.1 ± 2.6
Bottom	Not amended							
Top	Not amended	6.5 ± 0.0	3,786 ± 307	1,175.7 ± 103.9	388.9 ± 48.3	392.5 ± 38.6	16.0 ± 1.7	262.7 ± 18.9
Bottom	Amended							
Top	Amended	4.1 ± 0.1	1,000 ± 123	250.5 ± 40.7	40.0 ± 11.7	69.6 ± 12.7	4.0 ± 0.3	129.7 ± 9.7
Bottom	Not amended							
Top	Amended	6.6 ± 0.1	4,019 ± 263	1,244.1 ± 97.9	400.2 ± 39.2	411.6 ± 34.9	12.3 ± 1.9	269.2 ± 18.9
Bottom	Amended							
$LSD_{0.05}$		0.1	336	117.9	50.2	42.5	2.1	22.6
1 water:1 substrate extract	Not amended	4.6 ± 0.2	56.1 ± 4.8	0.4 ± 0.1	0.0 ± 0.0	0.1 ± 0.0	0.7 ± 0.0	10.2 ± 0.6
	Amended	6.8 ± 0.1	897.0 ± 60.0	250.9 ± 13.5	63.1 ± 46.2	64.5 ± 27.7	3.6 ± 1.4	67.5 ± 3.0
P value		<0.0001	<0.0001	<0.0001	<0.0241	<0.0001	<0.0001	<0.0001

analytical methods. The EC of extract from the pour-through should represent pore-water EC that is immediately available to plant roots. In contrast, the ≈70 mL of substrate solution (∼70% moisture content of a 100-g substrate sample) in the 1:1 water extract procedure was diluted by 250 mL of water thus yielding values 75% to 80% lower than the pour-through procedure. Others have also shown higher pour-through values compared directly with 1:1 water extract values (Wright et al. 1990; Yeager et al. 1983), although the difference in these cited experiments could not be attributed solely to dilution due to insufficient description on the saturation level of the extraction procedures.

EC of containers with amended substrate in the bottom half was similar regardless if the top was amended (4019 μS·cm^{-1}) or non-amended (3786 μS·cm^{-1}). Containers filled entirely with nonamended substrate had the lowest EC (209 μS·cm^{-1}) when using the pour-through, whereas those with only the top half amended had intermediary EC (1000 μS·cm^{-1}) indicating movement or transport of soluble salts from the top half to the bottom half either during the saturation or displacement phase (Table 2).

Pore-water nitrate followed a pattern similar to EC. Across all samples analyzed, nitrate and EC were highly correlated (R^2 = 0.9989, n = 24). Similar to EC, the highest pore-water nitrate readings when extracted with the pour-through were in containers with bark amended in the bottom half of the container, while the lowest pore-water nitrate concentrations were in containers with nonamended bark on the bottom (Table 2). Similar to EC, containers with nonamended bark on the bottom and amended bark on the top had slightly elevated pore-water nitrate levels indicating some movement of nitrate into the container bottom, although this value was still ∼80% lower than containers with amended bark in the bottom half. Similar to EC readings, nitrate pore-water concentration from pour-through extracts of containers that were either filled completely with amended bark or nonamended bark had higher nitrate concentrations than their 1:1 water extract counterparts.

Pore-water ammonium, phosphate, and potassium followed a similar trend to EC and nitrate with regard to higher concentrations from containers with amended bark in the bottom half of the container and lower concentrations than those that were nonamended in the bottom half.

Stratified substrate at potting. Pour-through extract results for stratified substrates closely reflected those of the conventional substrates. Pore-water pH determined by the pour-through in containers when both the top and bottom strata were nonamended was 4.7, compared with 5.0 for either textured substrate measured by the 1:1 water extract (Table 3). Likewise, pH of containers when both strata were amended with dolomitic lime was 6.6 as determined by the pour-through procedure, and 6.8 with 1:1 water extract, identical to results from the conventional substrates (Table 1). As in the CONV substrate, there is a 0.2-pH unit difference when comparing substrate pore-water pH when extracted with the pour-through vs. 1:1 water extract method regardless of pine bark texture.

When the bottom half of the containers were filled with nonamended substrate, pore-water pH determined with the pour-through was 4.4 and 4.7 when the top portion of the bark was amended and nonamended, respectively. Similar to conventional substrates, stratified

Table 3. Substrate pore-water pH, electrical conductivity (EC), nitrate (NO_3^-), ammonium (NH_4^+), dissolved inorganic nitrogen (DIN; $NH_4 + NO_3 + NO_2$), phosphate phosphorus (PO_4^--P), and potassium (K) concentration as measured with the pour-through procedure on stratified containers that were filled either halfway or fully with either a fine (FINE) or coarse (CRSE) pine bark substrate amended (+A) with pulverized dolomitic lime and 18N–2.2P–6.6K 3- to 4-mo controlled release fertilizer or a without amendment (−A). Separate samples of the amended or nonamended bark were also analyzed for the same parameters using the 1:1 water extract procedure. Data are presented as the mean ± 95% confidence interval (n = 6). LSD = least significant difference.

Top or bottom half of container	Substrate type	pH	EC	NO_3^-	NH_4^+	DIN	PO_4^--P	K
Top	FINE −A	4.7 ± 0.1	118 ± 10	1.5 ± 2.2	0.0 ± 0.0	0.3 ± 0.5	5.2 ± 0.3	27.7 ± 4.2
Bottom	CRSE −A							
Top	FINE −A	6.5 ± 0.0	3274 ± 353	1006.9 ± 181.6	337.9 ± 64.9	490.2 ± 91.4	48.7 ± 15.7	225.2 ± 41.3
Bottom	CRSE +A							
Top	FINE +A	4.4 ± 0.1	966 ± 113	280.0 ± 55.2	68.0 ± 22.7	116.1 ± 30.0	13.5 ± 2.9	103.4 ± 5.6
Bottom	CRSE −A							
Top	FINE +A	6.6 ± 0.1	4830 ± 599	1649.9 ± 159.0	98.6 ± 253.4	449.2 ± 174.3	94.5 ± 16.7	354.5 ± 36.9
Bottom	CRSE +A							
$LSD_{0.05}$		0.1	530	142.1	150.7	114.3	13.2	32.1
1 water: 1 substrate extract before potting	FINE −A	5.0 ± 0.1	46.2 ± 6.7	0.5 ± 0.2	0.0 ± 0.0	0.1 ± 0.0	0.9 ± 0.5	8.0 ± 0.4
	FINE +A	6.8 ± 0.0	696.9 ± 111.6	160.5 ± 7.4	65.6 ± 3.1	58.0 ± 2.4	3.4 ± 0.6	45.0 ± 2.3
	CRSE −A	5.0 ± 0.2	31.8 ± 0.7	0.6 ± 0.1	0.0 ± 0.0	0.1 ± 0.0	0.6 ± 0.0	5.3 ± 0.4
	CRSE +A	6.8 ± 0.0	1275.7 ± 166.2	354.6 ± 11.4	0.0 ± 0.0	80.3 ± 2.6	6.3 ± 1.1	84.5 ± 6.1
$LSD_{0.05}$		0.1	151	10.3	2.3	2.7	1.0	4.9

containers with the top half of the substrate amended with a high dolomitic lime rate showed no evidence of elevated pH suggesting that the pore-water extracted via the pour-through was primarily from the bottom portion of the container.

Pore-water EC from pour-throughs of containers in which both strata were nonamended was 118 $\mu S \cdot cm^{-1}$, compared with just 46.2 or 31.8 $\mu S \cdot cm^{-1}$ for nonamended FINE or CRSE bark analyzed by 1:1 water extract (Table 3). Pore-water EC of containers with the CRSE strata amended in the bottom half was higher if the top was amended (4830 $\mu S \cdot cm^{-1}$) than when nonamended (3274 $\mu S \cdot cm^{-1}$). Containers filled entirely with nonamended substrate had the lowest pore-water EC at 118 $\mu S \cdot cm^{-1}$, whereas those with only the top half amended had intermediary EC (966 $\mu S \cdot cm^{-1}$). Similar to containers filled completely with CONV substrate, this indicates diffusion or movement of soluble salts across strata (from the top layer to the bottom layer) during either the saturation or displacement phase.

The highest pore-water nitrate readings were in containers with both strata amended, whereas the lowest readings were in containers with both strata nonamended. Similar to conventional substrates, containers with nonamended bark on the bottom and amended bark on the top had slightly elevated pore-water nitrate levels indicating some movement of nitrate into the container bottom. Pore-water nitrate in pour-through extracts from containers that were filled completely with either amended bark or nonamended bark had much higher concentrations than their 1:1 water extract counterparts (Table 3).

Pore-water phosphate concentration was lowest and similar in the two treatments in which the bottom strata was not amended. Pore-water phosphate was higher in containers with both strata amended (30.8 $mg \cdot L^{-1}$) compared with containers with just the bottom strata amended (15.9 $mg \cdot L^{-1}$) (Table 3). Potassium was similar in this respect, in that among containers with the bottom strata amended, concentrations were higher when the top strata was also amended. Therefore, ions behaved similarly, regardless if anion or cation, having little electrochemical interaction with the pine bark substrate. This highlights a potentially important trend between the conventional containers and the stratified containers. Among conventional containers, all measured values were similar between the two treatments in which the bottom layer was amended regardless of whether the top was amended (except for phosphate, where pore-water concentration was higher when the top was not amended) (Table 3). In contrast, among stratified containers, those with both strata amended had higher levels of EC, nitrate, phosphate, and potassium than those with only the bottom strata amended (Table 3). This suggests that some aspect of solute transport in the stratified container made it more conducive for mineral nutrients to migrate from the top of the container to the bottom. However, literature has shown that pour-through extracts result in lower EC if fertilizer is placed in the top half of the container in

Table 4. Substrate pore-water pH, electrical conductivity (EC), nitrate (NO_3^-), ammonium (NH_4^+), dissolved inorganic nitrogen (DIN; $NH_4 + NO_3 + NO_2$), phosphate phosphorus (PO_4-P), and potassium (K) concentration as measured with the pour-through procedure (across vertical profile and bulk solution) and with the saturated media extraction (SME) procedure of the top and bottom halves of the vertical profile in traditional (<12.6 mm) and stratified pine bark substrate 42 d after potting. All stratified substrate constructs were composed of <6.3-mm size fraction above a 12.6 > 6.3-mm size fraction of pine bark. Substrate was amended with pulverized dolomitic lime and 18N–2.2P–6.6K 3- to 4-mo controlled release fertilizer or without amendment to create desired chemical properties. Data are presented as the mean ± 95% confidence interval (n = 5). LSD = least significant difference.

Substrate	Amendment	Pour-through: pH	EC	NO_3^-	NH_4^+	DIN	PO_4-P	K	Location	1:1 water: pH	EC	NO_3^-	NH_4^+	DIN	PO_4-P	K
Traditional substrate	Not amended	5.2 ± 0.0	64.8 ± 5.4	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.6 ± 0.5	16.1 ± 0.5	Top	5.4 ± 0.1	19.2 ± 3.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.1
									Bottom	5.6 ± 0.1	23.0 ± 2.7	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.4 ± 0.1
	Not amended	5.8 ± 0.1	1,775.3 ± 185.8	779.5 ± 84.1	17.3 ± 8.0	189.2 ± 25.7	21.9 ± 4.6	199.6 ± 23.9	Top	5.2 ± 0.2	67.3 ± 18.6	20.9 ± 8.2	0.0 ± 0.0	4.7 ± 2.3	0.0 ± 0.0	6.0 ± 2.4
									Bottom	5.7 ± 0.1	586.1 ± 18.1	274.7 ± 23.0	4.8 ± 1.1	65.4 ± 6.7	8.1 ± 1.4	60.7 ± 6.7
	Amended	4.4 ± 0.1	1,892.8 ± 289.9	821.6 ± 116.2	10.8 ± 17.2	189.9 ± 26.4	12.9 ± 2.6	193.7 ± 26.3	Top	5.6 ± 0.0	675.0 ± 31.4	263.0 ± 28.5	10.2 ± 1.6	64.5 ± 7.4	7.7 ± 0.7	61.1 ± 4.0
									Bottom	4.5 ± 0.1	544.1 ± 56.5	186.0 ± 83.5	25.5 ± 2.4	50.3 ± 23.7	3.2 ± 0.9	51.7 ± 5.5
	Amended	5.2 ± 0.1	4,397.0 ± 324.6	1977.6 ± 233.6	0.0 ± 0.0	452.0 ± 61.5	45.6 ± 6.2	373.0 ± 43.8	Top	5.7 ± 0.1	728.6 ± 120.5	276.7 ± 41.2	18.3 ± 6.6	71.2 ± 11.9	8.3 ± 2.1	64.3 ± 11.9
									Bottom	5.5 ± 0.1	967.6 ± 87.9	444.2 ± 71.2	23.7 ± 9.3	110.3 ± 16.8	12.5 ± 1.8	94.6 ± 8.4
	$LSD_{0.05}$	0.1	500.3	289.8	NS	61.9	7.0	59.6		0.2	116.0	86.7	8.3	19.4	5.8	12.4
Stratified substrate	Not amended	5.4 ± 0.1	46.2 ± 9.7	0.0 ± 0.0	NS	0.0 ± 0.0	0.6 ± 0.2	11.4 ± 2.8	Top	5.6 ± 0.1	22.9 ± 7.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.0	0.3 ± 0.2
									Bottom	5.6 ± 0.1	19.5 ± 1.3	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.0	11.4 ± 0.1
	Not amended	5.5 ± 0.2	1,607.5 ± 413.0	682.4 ± 75.6	7.7 ± 5.0	158.6 ± 16.1	17.1 ± 5.1	156.3 ± 46.4	Top	5.4 ± 0.2	48.9 ± 8.5	98.6 ± 169.1	3.9 ± 7.6	23.7 ± 41.0	2.5 ± 4.9	19.7 ± 33.2
									Bottom	5.6 ± 0.1	702.0 ± 76.3	250.1 ± 159.0	10.4 ± 8.0	60.6 ± 38.9	10.8 ± 7.6	61.6 ± 39.3
	Amended	4.2 ± 0.1	1,678.3 ± 397.8	810.2 ± 201.3	20.7 ± 4.5	190.1 ± 45.3	11.8 ± 3.4	163.1 ± 35.3	Top	5.6 ± 0.1	643.1 ± 120.8	302.0 ± 58.2	8.4 ± 6.7	72.1 ± 15.7	5.7 ± 1.0	48.8 ± 9.6
									Bottom	4.8 ± 0.1	251.8 ± 43.1	97.3 ± 18.5	5.8 ± 0.9	23.9 ± 4.4	0.2 ± 0.1	29.7 ± 2.8
	Amended	5.4 ± 0.2	3,918.8 ± 903.7	1,612.3 ± 484.4	0.0 ± 0.0	367.2 ± 110.3	28.5 ± 7.4	374.8 ± 90.9	Top	5.8 ± 0.2	615.4 ± 51.6	294.6 ± 49.0	4.5 ± 3.1	68.1 ± 11.6	6.2 ± 1.3	48.2 ± 7.7
									Bottom	5.6 ± 0.1	1002.4 ± 193.3	533.6 ± 115.3	14.5 ± 8.3	125.7 ± 28.7	13.1 ± 3.6	99.4 ± 21.9
	$LSD_{0.05}$	0.2	841.4	416.6	5.3	94.6	7.5	84.9		0.2	131.6	142.6	8.3	35.0	5.2	30.2

Table 5. Correlation coefficient between pore-water pH, electrical conductivity (EC), nitrate (NO_3^-), ammonium (NH_4^+), dissolved inorganic nitrogen (DIN; $NH_4 + NO_3 + NO_2$), phosphate phosphorus (PO_4^--P), and potassium (K) concentration from the pour-through procedure to the 1:1 water extract procedure conducted in either the top or bottom half of the container 42 d after potting. Traditional (<12.6 mm) or stratified pine bark substrates, fine (< 6.3 mm) atop coarse (12.6 > 6.3 mm), were amended with pulverized dolomitic lime and 18N–2.2P–6.6K 3- to 4-mo controlled release fertilizer or without amendment. NS refers to correlation being nonsignificant.

Parameter	Conventional		Stratified	
	Top	Bottom	Top	Bottom
pH	−0.5759	0.9233	NS	0.9501
EC	0.6934	0.9319	0.6454	0.8701
NO_3^-	0.6980	0.9048	0.6580	0.8044
NH_4^+	NS	NS	NS	NS
DIN	0.7282	0.9181	0.6452	0.7971
PO_4^--P	NS	0.9123	NS	0.7895
K	0.6840	0.9453	0.5472	0.8742

traditional (Ammons et al. 2022) or in a stratified substrate (Fields et al. 2022). This could be because of the distance the applied water travels and displaces (if piston flow occurs) or mixes the resident solution in the substrate as illustrated herein, or because of decreased infiltration rate, preferential flow, and water velocity when stratifying substrate (Criscione et al. 2022b).

Conventional substrates after 42 d. By 42 d after potting, salts from the distinct layers created within the pot would have had time to move up within the container profile by diffusion and with capillary water, or more likely, down through the profile with irrigation water and gravity.

Pore-water pH via pour-through extraction was lowest in containers that were amended in the top half but not in the bottom (Table 4). In these containers, the bottom half of the container would not have been amended with lime and thus not buffered against changes in pH. Furthermore, mineral nutrients in the pore-water from the amended upper half of the container would have moved downward into the bottom and acidified the substrate. This is especially evidenced by the high pore-water ammonium concentrations in the bottom half of the container as determined by the 1:1 water extract procedure, all of which must have originated in the top half. Conversion of the ammonium to nitrate will acidify the pore-water. The 1:1 water extract analysis of the top and bottom halves of these containers showed that the mean pore-water pH of the two halves still differed by 1.1 pH units. The pour-through extract most closely reflects the pore-water pH of the bottom half of the container, and considering their overlapping 95% CIs, it could reasonably be concluded that those values are similar. Conversely, pore-water pH was highest in containers that were amended in the bottom half but not the top. These containers would have pH adjusted by the lime additions, and although fertilizer salts should be present in the pore-water to acidify the substrate, a greater proportion of those salts would have leached from the container due to being in closer proximity to drainage holes in the container bottom. The pore-water extracted via 1:1 extract showed that these containers too had different pH in the bottom and top portions of the container, with pour-through extract most closely reflecting the bottom portion of the container with overlapping 95% CI ranges. Pour-through determined pH was similar and intermediary in containers that were filled either entirely with amended or nonamended substrate. Containers that were entirely nonamended would have been poorly buffered against change in pH, thus increasing pH from the beginning of the experiment would have been caused by irrigation water alkalinity. Containers that were filled entirely with amended substrate would have counteracting effects of fertilizer acidity and lime basicity, thus pH in these containers decreased from the start of the experiment. Finally, pore-water pH as determined by the pour-through was highly correlated to pH determined by 1:1 water extract in the bottom half of the container (r = 0.9233) and poorly correlated with an inverse relationship to pH measured by 1:1 water extract in the top half of the container (r = −0.5759, Table 5).

Pore-water EC values reflected the percentage of the container filled with amended substrates (Table 4). Containers that were filled completely with nonamended substrate had the lowest EC, and those filled entirely with amended substrate had the highest EC. Containers filled with amended substrate in either half had similar and intermediary pore-water EC levels. This was to be expected, as the mineral nutrients released from the CRF would migrate easily throughout the container, especially from the top half to the bottom of the container as irrigation water moved downward. Despite this, pore-water EC levels from the pour-through were still more highly correlated with 1:1 water extract EC from the bottom part of the container (r = 0.9319) than the top (r = 0.6934) (Table 5).

Pore-water nitrate followed a pattern similar to EC with respect to pour-through extracts (Table 4). Similar to EC, pore-water nitrate concentrations extracted via the pour-through were more highly correlated to 1:1 water extract from the bottom half of the container (r = 0.9048) than the top half (r = 0.6980) (Table 5). Pore-water ammonium concentrations were erratic within a treatment and not significantly different among treatments, nor were pour-through concentrations correlated to 1:1 water extract from the bottom or top halves of the container. Even containers

amended with CRF in both the top and bottom of the container had no detectable pore-water ammonium in pour-throughs. Niemiera and Wright (1987a) reported rapid nitrification in containers in which application of 100 mg·L^{-1} ammonium resulted in leachates with only 2 to 4 mg·L^{-1} ammonium in just 6 d. Furthermore, based on nitrate accumulation rates in pine bark substrates, it was projected that a 40-mg·L^{-1} ammonium solution could be completely oxidized in 20 h (Niemiera and Wright 1987b).

Phosphate and potassium pore-water concentrations followed the same trend. Both were highest in containers that were filled with amended substrate, lowest in containers completely filled with nonamended substrate, and intermediary in containers only half filled with amended substrate (Table 4). Pore-water phosphorus extracted via pour-throughs was highly correlated to 1:1 water extract phosphate concentrations in container bottoms (r = 0.9312) but not correlated to 1:1 water extract from the top half of the container (Table 5). Pore-water potassium concentrations, when extracted by the pour-through method, were correlated to both the top and bottom containers, but the correlation coefficient was higher with the container bottom.

Stratified substrates at 42 d. Similar to conventional containers, pour-through pH was lowest in containers that were amended in the top half but not in the bottom (Table 4). The pour-through procedure in this treatment most closely reflects the 1:1 water extract pH of the bottom half of the container. Pore-water pH in all other stratified treatments was similar when extracted by the pour-through method. The 1:1 water extract pH in the top and bottom halves of the other stratified treatment were similar within a treatment with few discernible patterns. The lowest pore-water pH across traditional and stratified containers occurred when the top was amended and bottom was not amended; however, there is no direct indication of why this phenomenon occurs because EC, dissolved organic nitrogen, phosphorus, and potassium concentrations were intermediary to their amended or nonamended counterparts. Regardless, pour-through extracted pH was highly correlated to 1:1 water extract pH in the bottom half of the container (r = 0.9501), but not correlated to 1:1 water extract pH in the top half.

Similar to CONV substrate, pore-water EC values reflected the percentage of the container filled with amended substrates (Table 4). Containers that were filled completely with nonamended substrate had the lowest EC, and those filled entirely with amended substrate had the highest EC. Containers filled with amended substrate in either half had similar and intermediary pore-water EC. Despite this, pore-water EC levels from the pour-through were still more highly correlated with 1:1 water extract EC from the bottom part of the container (r = 0.8701) than the top (r = 0.6454) (Table 5).

Pore-water nitrate in stratified substrates followed a similar pattern to EC with respect to pour-through extracts and were more highly correlated to 1:1 water extract from the bottom

half of the container (r = 0.8044) than the top half (0.6580) (Table 5). Ammonium concentrations were erratic. And similar to CONV substrates, ammonium was only detected in substrates that were amended in either the top or bottom, and completely undetected in substrates that were filled entirely with amended or nonamended substrates. Pour-through extract concentrations were not correlated to 1:1 water extract from either half of the container.

Pore-water phosphate and potassium concentrations followed the same trend when using the pour-through extract. Both were highest in containers that were filled with amended substrate, lowest in containers completely filled with nonamended substrate, and intermediary in containers only half filled with amended substrate (Table 4). Phosphorus concentration in pour-through extracts was highly correlated to 1:1 water extract concentrations in container bottom (r = 0.9312), but not correlated to 1:1 water extract from the top half of the container (Table 5). Pore-water potassium concentrations when using pour-through extracts were correlated to 1:1 water extracts from both the top and bottom containers, but the correlation coefficient was higher with the container bottom.

Conclusion

Practitioners of the pour-through procedure typically aim to acquire a 50-mL sample (Altland 2021). Ideally, this sample would be representative of the chemical properties of the entire container profile. The data presented here demonstrate that the pour-through procedure is heavily biased toward the chemical properties of the lower half of the container profile. Within the confines of the pour-through procedure, there does not seem to be a simple solution to this issue. Because of the uneven movement of water or hydrodynamic dispersion through saturated or unsaturated containers (i.e., preferential flow), applying additional water will likely result in contamination of the extracted sample by the displacement solution (Hoskins et al. 2014b). Others have suggested use of suction lysimeters or soil moisture samplers for extracting substrate solutions from containers (Cabrera 1998; Jeong et al. 2012; Stanley et al. 2003), but even these will extract solutions from a localized region in the container. Likewise, Jeong et al. (2012) reported gradients in pH, EC, and volume of extractable solution along the vertical profile when using a Rhizon soil moisture sampler.

The upper and lower halves of the containers in this research were intentionally amended with or without lime and fertilizer to exaggerate differences in the chemical properties of the two halves and more clearly identify which portion of the container was reflected in pour-through results. Among containers with only the top half of the substrate amended, sampling after 42 d when salts would have migrated or moved downward to the container bottom, correlation analysis showed that pour-through results still reflect the chemical properties of the container bottom. Considering the gradient in pH and soluble salts

that occur in container crops, there may be no single method of extracting substrate solution that accurately reflects the chemical properties of the entire container.

The objective of this research was to determine if the pour-through procedure is biased by preferentially extracting substrate solution near the bottom of the container in both uniformly filled containers as well as intentionally stratified containers. Evidence herein demonstrates conclusively that the pour-through procedure is more reflective of the lower half of the container than the upper half for both CONV and stratified substrates. The pour-through procedure still yields useful information, but that information should be considered in the context of how the sample was collected and that the results may not reflect conditions throughout the entire container. Substrates that are poorly buffered to changes in pH are fertilized exclusively from the top or bottom of the container with water-soluble fertilizers, or have high water holding capacity (and thus a more pronounced zone of saturation at the container bottom resulting in anaerobic conditions), and may be more prone to variations in pH and nutrient availability from the top to the bottom of the container. Likewise, containers that are topdressed with CRFs, or intentionally stratified in some other way, are also more prone to variation in chemical properties throughout the container profile. Caution should be used in all of these cases when interpreting pour-through results.

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