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Methods of Constructing a Pine Tree Substrate from Various Wood Particle Sizes, Organic Amendments, and Sand for Desired Physical Properties and Plant Growth

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Abstract. The use of freshly harvested and processed pine trees as a container substrate for greenhouse and nursery crop production is a relatively new concept, and fundamental knowledge of the construction of a pine tree substrate (PTS) for optimal physical properties is insufficient. Therefore, this research was conducted to determine the influence of mixing PTSs produced with different wood particle sizes and adding other amendments to PTS on substrate physical properties and plant growth compared with traditional substrates. Coarse pine wood chips produced from 15-year-old loblolly pine trees (*Pinus taeda* L.) were ground in a hammermill fitted with either a 4.76-mm screen or with no screen (PTS-NS) allowing a fine and a coarse particle PTS to be produced. Increasing proportions of the finer (4.76-mm) PTS to the coarser PTS (PTS-NS) resulted in increased container capacity (CC) and shoot growth of 'Inca Gold' marigold (*Tagetes erecta* L.). In another study, PTSs were manufactured in a hammermill fitted with different screen sizes: 4.76, 6.35, 9.54, or 15.8 mm as well as PTS-NS. After being hammermilled, each of the five PTSs was then amended (by mixing) with 10% sand (PTS-S), 25% peatmoss (PTS-PM), or left unamended. Pine tree substrates were also produced by adding 25% aged pine bark (PB) to pine wood chips before being ground in a hammermill with each of the five screen sizes mentioned (PTS-HPB). These five substrates were used unamended as well as amended with 10% sand after grinding (PTS-HPBS). Control treatments included peat-lite (PL) and 100% aged PB for a total of 27 substrates evaluated in this study. Container capacity and marigold growth increased as screen size decreased and with the additions of peatmoss (PTS-PM) or hammering with PB (PTS-HPB) to PTS. Container capacity for all substrates amended with peatmoss or PB was within the recommended range of 45% to 65% for container substrates, but only with the more finely ground PTS-4.76-mm resulted in marigold growth comparable to PL and PB. However, when the PTS-NS was amended by mixing in 25% peat or hammering with 25% PB, growth of marigold was equal to plants grown in PL or PB. In a third study, hammering PTS-NS with 25% PB followed by the addition of 10% sand increased dry weight of both azalea (*Rhododendron ×hybrida* 'Girard Pleasant White') and spirea (*Spiraea nipponica* Maxim. 'Snowmound') resulting in growth equal to plants grown in 100% PB. This work shows that amending coarsely ground PTS with finer particle PTS or with other materials (peatmoss, aged PB, or sand) can result in a substrate with comparable physical properties such as CC and plant growth compared with 100% PL or PB.

Recent work demonstrating the successful use of pine tree substrates (PTS) for greenhouse and nursery crop production has gained considerable interest from growers and substrate manufacturers. Pine tree substrates can be produced from pine trees that are chipped and ground (with or without bark, limbs, needles, and so on) in a hammermill or from clean chip residual (CCR: ≈40% pine wood, 50% bark, and 10% needles), which is produced from byproducts of the pine tree-harvesting process (Boyer et al., 2006; Fain et al., 2006; Laiche and Nash, 1986; Wright and Browder, 2005). Although pine bark (PB) is a product/component of pine trees, for the purpose of describing pine wood-based substrates that have recently been investigated, it is not considered to be a PTS because it does not contain an appreciable percentage of wood. It has been shown that pine wood chips that are hammermilled into a PTS with a particle size range and physical properties comparable to aged PB and peat-based substrates are acceptable for

use as a container substrate (Jackson and Wright, 2009b; Jackson et al., 2008b; Saunders et al., 2006; Wright et al., 2008b). Research with various PTSs and CCR has also shown that a wide variety of nursery (Boyer et al., 2009; Jackson et al., 2008a; Wright et al., 2006) and greenhouse (Boyer et al., 2008; Fain et al., 2008a; Jackson et al., 2008b; Wright et al., 2008a) crops can be produced with similar quality to plants grown in peatmoss or PB.

The southern United States, which produces 60% of the nation's timber products and more timber than any other country in the world, has been quoted as being the "woodbasket of the world" as a result of increasing productivity of pine plantations, in particular loblolly pine (Prestemon and Abt, 2002). Research by Samuelson et al. (2008) showed that short-rotation pine plantations in the southern United States would better exploit the genetic growth potential of loblolly pine. The short rotation/production of loblolly pines used for producing PTS (10 to 15 years) could potentially open a significant avenue for maximum use of young pine plantations in the southeast. In addition to the production of PTS from loblolly pines, additional research by Fain et al. (2008a) has shown that slash pine (*Pinus elliottii* Engelm.) and longleaf pine (*Pinus palustris* Mill.) are potential tree species for producing PTSs in the southern United States. Wright et al. (2009) reported that eastern white pine (*Pinus strobus* L.) could also serve as a source of pine for PTS production, which could be potentially significant to the greenhouse and nursery industry in the northeastern United States where loblolly pine cannot be grown.

Some advantages of PTS are: 1) PTS can be produced in close proximity to growers and substrate companies where pine trees are abundant, which minimizes transportation costs of long-distance shipping; 2) PTS can be used immediately after milling and does not have to be composted or aged before use as a container substrate; and 3) physical properties such as container capacity (CC) and air space (AS) can be easily altered during the manufacturing process to meet the needs of particular plants and container sizes by the degree of pine wood chip grinding in a hammermill. For example, Jackson and Wright (2009a) and Saunders et al. (2006) demonstrated that AS ranged from 18% to 39% for PTS ground in a hammermill with screens ranging in size from 1.6 mm to 6.35 mm, respectively. An AS range of 10% to 30% is recommended for container plant production (Yeager et al., 2007). Container capacity of those same substrates ranged from 43% to 65%, which is near or within the range of 45% to 65% normally considered acceptable for substrates. Marigold plants (*Tagetes erecta* Big. 'Inca Gold'), grown in a 100% PTS with 18% AS and 65% CC (produced with a 1.6-mm hammermill screen), were as large as plants grown in a peat-lite [PL; 80% peatmoss/20% perlite (v/v)] substrate that had similar AS and CC (16.8% and 65%, respectively; Saunders

et al., 2006). These results demonstrate that a 100% PTS can be produced with physical properties similar to commercial substrates if ground finely enough and that plant growth in 100% PTS is comparable to growth in traditional peat-based substrates.

However, producing a PTS with a particle size fine enough to possess an adequate water-holding capacity similar to peatmoss or aged PB may be too costly as a result of expenses associated with grinding (primarily energy costs). Another approach would be to mix larger PTS particles with various proportions of fine PTS particles (less than 0.5 mm), which could result in a PTS with adequate CC and AS. Research with 100% PB substrates has shown that substrate particles smaller than 0.5 mm (fines) greatly influence the physical properties (AS and CC) in containers (Handreck, 1983) and that considerable variation in the proportions of substrate particles larger than 0.5 mm have a minor influence on the physical properties (AS and CC). The intermixing of various PTS particle sizes should result in reduced production costs for PTS because relatively small amounts (percentage) of finely ground PTS (more costly to produce than coarsely ground PTS) would be needed to supply enough fines to give desired CC of the substrate. Another approach to increasing CC by adding fine particles would be to amend large-particle PTS with peatmoss, aged PB, sand, or other organic or inorganic materials that characteristically have a high percentage of fines. The additions of peatmoss or aged PB would also increase the cation exchange capacity (CEC) of PTS which is low (2.1 cmol·L^{-1}; Wright et al., 2008a) compared with peatmoss and aged PB: 10 and 12 cmol·L^{-1}, respectively (Nelson, 2003). Increasing CEC could help reduce extra nitrogen (N) requirements needed for plant growth in 100% PTS compared with peatmoss or PB (Wright et al., 2008a). In support of this approach, Jackson et al. (2008b) showed that adding 25% peatmoss (v/v) to PTS ground through a 4.76-mm hammermill screen increased CC and growth of poinsettia compared with 4.76 mm PTS without peat additions. There is also evidence that plants grown in peat-amended PTS require less N for optimal growth than plants grown in PTS without peat (Jackson and Wright, 2009c).

Sand is one of the most commonly used inorganic amendments in soilless container substrates because it provides ballast and can help overcome rewetting problems (Guttormsen, 1974). Combing sand with organic components decreases the infiltration (the downward entry of water through the substrate surface and into the substrate) rate of irrigation water as it moves through the substrate profile, particularly in fresh or less decomposed organic components (Bilderback and Jones, 2001). Water percolation (the downward movement of water through the substrate profile/container) rate also decreases as the percentage of sand increases in a PB and sand substrate mixture (Brown and Pokorny, 1975). The slower infiltration rate of water in sand-amended substrates promotes more thorough wetting of the substrate compared with a 100% organic substrate in which water can channel rapidly to the bottom of the container (Bilderback and Jones, 2001).

The formation/engineering of substrates for greenhouse and nursery crop production has been achieved several times since soilless media began being the primary substrate in container production including the University of California (UC) mixes (Matkin and Chandler, 1957), Cornell "Peat-lite" mixes (Boodley and Sheldrake, 1964), and PB-based substrates (Krafka and Pokorny, 1979; Pokorny and Henny, 1984a, 1984b). Research with PB has thoroughly described the construction/engineering of 100% PB substrates and how its physical properties change when amended with other organic materials (Bilderback and Fonteno, 1993; Lemaire et al., 1980; Nkongolo et al., 2000; Tyler et al., 1993), mineral aggregates (Owen et al., 2007), clay (Handreck and Black, 2005), and inorganic materials (Brown and Pokorny, 1975; Raviv and Lieth, 2008). One cannot assume that wood-based substrates have the same physical properties as PB (aged or fresh) when constructed/formulated into a container substrate. Research has shown the range in physical properties of wood-based substrates (Boyer et al., 2009; Gruda and Schnitzler, 2004; Gruda et al., 2000; Jackson, 2008), but limited information is available on the manufacturing (and methods thereof) of wood-based substrates and how those methods influence physical properties. Previous research with nonwood-based substrates (peatmoss, aged and fresh PB, coir, compost) specify that a high proportion of particles in the range from 0.5 mm to ≈6.0 mm are needed to supply the appropriate air and water regimes. Numerous authors reported that substrate particles less than 0.5 mm (fines) are needed for adequate water-holding properties, and the recommend amount of these fines has ranged from 10% to 15% (Goodwin, 1980) to 36% (Thomas and Perry, 1980).

Because wood-based substrates will be more widely used in the trade, generating information about constructing/formulating a PTS (and any other wood-based substrates) to supply a substrate environment (air, water, and stability) for various crops and the array of grower operations is essential. Reproducible and economical construction of PTS is needed so that standardization of substrate processing may be imposed with consistent results. A knowledge of particle size distribution for a wood substrate can be used to characterize its expected physical properties and provide guidelines for how to process wood chips (hammermilling) to achieve the CC and AS desired for crop production. As a result, uniformity of plant production, be it greenhouse or nursery crops, should be enhanced and more predictable.

Based on the previous studies conducted on other substrates and works conducted on PTSs, a preliminary experiment was conducted to determine if grinding (hammering) a mixture of peatmoss or aged PB with unground pine chips would result in a more homogenous product (substrate). We found that mixing peatmoss (25%) with a coarsely hammered PTS (produced by hammering wood chips with no screen in the hammermill) was just as effective as grinding the peatmoss with the pine wood chips during PTS manufacturing in terms of increasing CC of the substrate and subsequent plant growth of marigold. However, hammering aged PB (25%) with pine wood chips was more effective in improving physical properties and plant growth than mixing PB with PTS after hammering. Based on these initial observations, the purpose of this work was to evaluate the influence of: 1) combining PTSs of different particles sizes; and 2) adding peatmoss, aged PB, and sand to PTSs of different particle sizes on substrate physical properties and plant growth.

Materials and Methods

Combining pine tree substrates of different particle sizes. Fifteen-year-old loblolly pine trees were harvested and delimbed on 10 May 2008 and chipped on 24 June with a Bandit Chipper (Model 200; Bandit Industries, Inc., Remus, MI). Coarse pine wood chips were ground on 24 June in a hammermill (Meadows Mills, Inc., North Wilkesboro, NC) fitted with either a 4.76-mm screen or with no screen (NS) with the latter resulting in a coarser PTS than with the screen. These two substrates were then combined at the following proportions: 100% 4.76 mm, 75% 4.76 mm:25% NS, 50% 4.76 mm:50% NS, 25% 4.76 mm:75% NS, and 100% NS. Control treatments of PL [80% peatmoss/20% perlite (v/v; Premier Tech, Quebec, Canada)] and 100% aged PB were included. Each substrate was amended with calcium sulfate (CaSO$_4$) at 0.6 kg·m^{-3}. Substrate pH for all PTS treatments was ≈6.0; therefore, no pH adjustment (lime addition) was necessary. Peat-lite and PB were amended with dolomitic limestone at 5.25 and 3.5 kg·m^{-3}, respectively, to raise pH to 6.0. On 27 June, 12-d-old marigold seedlings grown in 144-unit plug trays using Fafard Superfine Germinating Mix (Conrad

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Table 1. Physical and chemical properties of pine tree substrates (PTS), peat-lite, and pine bark and growth data for marigold grown for four weeks in 2008.[z]

Substrate	Container capacity[y] (% vol)	Air space[x] (% vol)	Available water[w] (% vol)	Percent fines[v] (% mass)	Shoot dry wt (g)	Growth index[u] (cm)	Root rating[t]	pH[s]	EC[sr] (dS·m⁻¹)
100%-PTS-4.76[q]	52.6 b[p]	36.3 de	35.7 a	14.9 a	9.8 ab	34.1 a	2.0 bc	5.3 e	1.5 b
75%-PTS-4.76	47.1 c	40.7 cd	31.9 ab	9.4 b	9.6 bc	34.2 a	1.5 cd	5.5 d	1.3 c
50%-PTS-4.76	43.3 c	43.8 bc	34.7 a	7.6 bc	9.1 cd	32.7 ab	2.2 bc	5.7 bc	1.3 c
25%-PTS-4.76	40.4 d	47.7 ab	26.8 bc	5.0 c	8.8 d	32.6 ab	2.7 ab	5.7 bc	1.2 c
100%-PTS-NS	35.7 e	49.2 a	23.8 c	2.3 d	8.1 e	31.9 bc	3.0 a	6.0 a	1.2 c
Peat-lite[o]	61.7 a	21.3 f	37.5 a	14.7 a	10.1 ab	30.9 c	1.2 d	5.6 c	2.0 a
Pine bark	48.0 c	33.0 e	27.8 bc	7.9 b	10.4 a	33.0 ab	1.2 d	5.8 b	1.3 c

[z]Physical properties data were collected from three samples per substrate and represented as means. Analysis performed using the North Carolina State University Porometer method (Fonteno et al., 1995).
[y]Container capacity is (wet weight – oven dry weight) ÷ volume of the sample.
[x]Air space is the volume of water drained from the sample ÷ volume of the sample.
[w]Available water = container capacity – unavailable water.
[v]Percent fines = percent mass of three oven-dried 150-g substrate samples less than 0.5 mm. 1 mm = 0.0394 inch.
[u]Growth index [(height + widest width + perpendicular width) ÷ 3].
[t]Root rating of 1 to 3 assigned to the rootballs of plants = 1 being the least amount of roots and 3 being the most amount of roots.
[s]pH and electrical conductivity (EC) of substrate solution obtained by the pour-through method (Wright, 1986).
[r]1 ds·m⁻¹ = 1 mmho/cm.
[q]PTS produced from 15-year-old loblolly pine trees that were harvested at ground level, delimbed, chipped, and hammermilled to pass through a 4.76-mm screen and mixed with PTS produced with no screen (NS) at 25% increments.
[p]Means separated within columns using Duncan's multiple range test ($P \leq 0.05$).
[o]Peat-lite composed of 80% peatmoss/20% perlite (v/v).

Fafard, Inc., Agawam MA) were transplanted into 10-cm square (l-L) plastic containers with the different substrates. Plants were glasshouse-grown in Blacksburg, VA, and fertilized at each watering with a 300 mg·L⁻¹ N solution (beaker-applied) from a Peters 20N–4.4P–16.6K Peat-Lite Special (The Scotts Co., Marysville, OH). Plants were irrigated throughout the study at the same time as determined by the general weight of containers and irrigated to achieve a 20% leaching fraction, which was determined in preliminary studies to be the most similar for all substrates considering their difference in CC percentages. Substrate solution was extracted using the pour-through (PT) method (Wright, 1986) on 15 July and analyzed for pH and electrical conductivity (EC) using a Hanna HI 9811 instrument (Hanna Instruments, Woonsocket, RI). Growth index [GI; (height + widest width + perpendicular width)/3] was determined on 22 July; shoots were severed at the substrate surface, oven-dried for 5 d at 65 °C, and dry weights recorded. The root ball of each plant was given a subjective (visual) root rating of 1 to 3 based on the density of roots on the outside/surface of the root ball with 1 being the least amount of roots and 3 being the most. The rating was given to each side of each root ball, of each plant, and averaged (n = 4). Physical properties including AS, CC, total porosity, and bulk density (BD) were determined on three replicate samples of each substrate using the North Carolina State University (NCSU) Porometer method as described by Fonteno et al. (1995). Available water was determined on substrates by calculating CC – unavailable water. Unavailable water (the amount of water held in the substrate at 1.5 MPa or greater) was determined with the 100-cm³ cores using the pressure plate extraction in a procedure developed by Milks et al. (1989).

The experimental design was completely randomized with seven substrates and eight replications per substrate for a total of 56 containers. Data were analyzed using SAS (Version 9.1; SAS Institute, Inc., Cary, NC) with treatment means separated by Duncan's multiple range test (α = 0.05).

Pine tree substrate with various amendments. Fifteen-year-old loblolly pine trees were harvested and delimbed on 27 Feb. 2008 and chipped on 25 Mar. with a Bandit Chipper. These coarse pine chips were further ground on 26 Mar. in a hammermill fitted with different screen sizes: 4.76, 6.35, 9.54, and 15.8 mm as well as one PTS hammered without any screen (NS; coarse texture) in place. Each of the five PTSs were then amended (mixed) by volume with 10% sand (PTS-S), 25% peatmoss (PTS-PM), or left unamended (PTS) for a total of 15 substrates. Additional substrates were produced by grinding (hammering) coarse pine wood chips with 25% aged PB (PTS-HPB) with each of the five hammermill screens mentioned. These five PTSs were then amended with 10% sand (PTS-HPBS) or left unamended for a total of 10 substrates. Control treatments included PL and 100% aged PB for a total of 27 substrates evaluated in this study. Each substrate was amended with $CaSO_4$ at 0.6 kg·m⁻³. Peat-lite and PTS-HPB substrates were amended with dolomitic limestone at 5.25 and 3.5 kg·m⁻³, respectively. On 15 Apr., marigold seedlings grown in 144-unit plug trays using Fafard Superfine Germinating Mix were transplanted into 10-cm square (l-L) plastic containers with the 27 different substrates. Plants were glasshouse-grown in Blacksburg, VA, and fertilized at each watering with a 300 mg·L⁻¹ N solution (beaker-applied) from a Peters 20N–4.4P–16.6K Peat-Lite Special (The Scotts Co.). Plants were irrigated throughout the study at the same time as determined by the general weight of containers and irrigated to achieve a 20% leaching fraction, which was determined in preliminary studies to be the most similar for all substrates considering their difference in CC percentages. Substrate solution was extracted using the

PT method on 23 Apr., 30 Apr., and 9 May and analyzed for pH and EC using a Hanna HI 9811 instrument. On 15 May, GI was determined and shoots were severed at the substrate surface, oven-dried for 5 d at 65 °C, and dry weights recorded. The root ball of each plant was rated as previously described.

Physical properties of each substrate were determined preplant on three replicate samples of each substrate using the NCSU Porometer method as described previously. Particle size distribution of 150-g oven-dried substrate samples was determined with 14 sieves (ranging from greater than 6.3 mm to less than 0.063 mm) plus a bottom pan. Sieves and pan were shaken for 10 min with a RX-29 Ro-Tap sieve shaker (278 oscillations/min, 150 taps/min; W.S. Tyler, Mentor, OH) and the particle fractions retained on each sieve and the amount that passed through the smallest sieve and retained by the sieve pan were weighed. As a result of small quantities of substrate particles on several of the sieve pans, and to simplify the presentation of data and discussion of results in this article, contents of sieve pans close in size to one another were combined resulting in a total of six sizes: greater than 2.0, 1.0, 0.5, 0.25, 0.125, and 0.063 plus the bottom pan.

The experimental design was completely randomized with 27 substrates and eight replications per substrate for a total of 216 containers. Data were analyzed with the analysis of variance procedure of SAS with treatment means separated by Duncan's multiple range test (α = 0.05). Data were also subjected to regression analysis using SigmaPlot (Version 9.01; SPSS, Inc., Chicago, IL).

Azalea and spirea growth in amended pine tree substrate. Fifteen-year-old loblolly pine trees were harvested on 14 Apr. 2008 and chipped on 16 Apr. with a Bandit Chipper. These coarse pine chips were further ground on 16 Apr. in a hammermill fitted with either a 9.35-mm screen or with no

Table 2. Particle size distribution of peat-lite (PL), pine bark (PB), and pine tree substrate (PTS) with various amendments.[z]

Screen size[w]	Greater than 2.0	1.0	0.5	0.25	0.125	0.063	Pan	Coarse	Medium	Fine
								Texture group (% mass)[x]		
	Sieve opening (mm)[y]									
					PTS[v]					
4.76 mm	9.2	46.9	26.5	10.5	5.6	1.2	0.1	9.2 e[u]	73.4 a	17.5 a
6.35 mm	20.5	51.2	17.6	6.8	3.4	0.6	0.0	20.5 d	68.7 b	10.8 b
9.35 mm	49.1	28.9	12.4	5.7	2.9	0.9	0.1	49.1 c	41.3 c	9.6 b
15.9 mm	63.5	22.1	8.7	3.4	1.7	0.4	0.1	63.5 b	30.8 d	5.7 c
No screen	69.2	16.0	8.3	3.6	2.1	0.7	0.1	69.2 a	24.4 e	6.4 c
					PTS-S[t]					
4.76 mm	4.2	30.8	20.5	29.4	13.8	1.2	0.0	4.2 c	51.4 a	44.5 a
6.35 mm	20.7	23.0	16.0	21.8	16.4	1.9	0.1	20.7 b	39.0 b	40.3 ab
9.35 mm	26.1	25.5	12.9	20.3	13.6	1.5	0.1	26.1 b	38.4 b	35.5 bc
15.9 mm	41.1	18.0	9.7	18.2	11.4	1.5	0.1	41.1 a	27.7 c	31.1 cd
No screen	46.6	18.8	8.9	14.5	9.8	1.4	0.1	46.6 a	27.7 c	25.7 d
					PTS-PM[s]					
4.76 mm	11.7	38.6	27.8	11.8	6.8	2.7	0.5	11.7 c	66.4 a	21.8 a
6.35 mm	23.4	43.7	17.4	8.3	4.9	2.0	0.4	23.4 b	61.1 b	15.5 b
9.35 mm	25.8	37.3	19.1	8.9	6.2	2.3	0.3	25.9 b	56.4 b	17.7 b
15.9 mm	51.1	19.9	11.7	8.7	5.8	2.3	0.6	51.1 a	31.6 c	17.3 b
No screen	55.0	16.9	11.5	8.2	6.0	2.0	0.5	55.0 a	28.4 c	16.7 b
					PTS-HPB[r]					
4.76 mm	2.5	29.8	34.2	19.2	11.2	2.8	0.4	2.5 e	64.0 b	33.5 a
6.35 mm	8.1	42.1	27.0	12.0	8.0	2.4	0.4	8.1 d	69.1 a	22.8 b
9.35 mm	18.1	44.9	20.4	10.2	5.1	1.2	0.1	18.1 c	65.4 ab	16.5 c
15.9 mm	48.6	20.6	13.2	9.4	6.5	1.4	0.2	48.6 b	33.8 c	17.6 c
No screen	63.4	15.6	9.7	6.0	3.9	1.1	0.3	63.4 a	25.3 d	11.4 d
					PTS-HPBS[q]					
4.76 mm	1.6	18.6	21.7	28.9	24.6	4.2	0.5	1.6 d	40.2 a	58.1 a
6.35 mm	8.1	25.4	19.2	27.1	18.2	1.9	0.1	8.1 d	44.6 a	47.3 b
9.35 mm	16.7	23.8	16.8	24.3	16.4	1.8	0.1	16.7 c	40.6 a	42.7 bc
15.9 mm	29.1	13.1	12.2	22.2	19.5	3.5	0.3	29.1 b	25.4 b	45.6 b
No screen	39.5	16.3	11.3	20.0	11.7	1.2	0.1	39.5 a	27.5 b	33.0 c
					Screen size (S)			≤0.0001	≤0.0001	≤0.0001
					Amendment (A)			≤0.0001	≤0.0001	≤0.0001
					S*A			≤0.0001	≤0.0001	≤0.0001
PL[p]	31.3	15.4	16.0	14.7	13.4	6.8	2.3	31.3	31.4	37.3
PB	52.6	21.2	14.7	7.1	3.0	1.1	0.3	52.6	35.9	11.5
Sand	0.0	0.2	6.6	39.8	43.6	8.9	0.9	0.0	6.8	93.2

[z]Values are means of three oven-dried samples.

[y]1 mm = 0.0394 inch.

[x]Texture grouping: coarse = greater than 2.0 mm; medium = greater than 0.5 to less than 2.0 mm; fine = less than 2.0 mm.

[w]Size of hammermill screens used to produce PTS.

[v]PTS produced from 15-year-old loblolly pine trees that were harvested at ground level, delimbed, chipped, and hammermilled.

[u]Means separated within column by Duncan's multiple range test ($P \leq 0.05$) (n = 3). Means followed by the same letter are not significantly different.

[t]PTS-S produced by amending PTS with 10% sand (9:1 ratio).

[s]PTS-PM produced by amending (mixed after grinding) PTS with 25% peatmoss (3:1 ratio).

[r]PTS-HPB produced by grinding fresh pine wood chips with 25% aged PB (3:1 ratio) in a hammermill.

[q]PTS-HPBS produced by amending 10% sand (9:1 ratio) to PTS-HPB.

[p]PL composed of 80% peatmoss/20% perlite (v/v).

screen in place (NS). Both substrates were amended (by vol) with 10% sand (PTS-S) or left unamended (PTS). Additionally, substrates were produced by hammering coarse pine chips together with 25% aged PB (PTS-HPB) using either the 9.35-mm screen or no screen method as mentioned previously. The PTS-HPB was left unamended or amended with 10% sand (PTS-HPBS). Control treatments included 100% PB and PB plus 10% sand (PB-S) for a total of 10 substrates. Each substrate was amended with $CaSO_4$ at 0.6 kg·m^{-3}, and the PB used was amended with dolomitic limestone at 3.6 kg·m^{-3} before grinding with the wood chips. On 17 Apr., liners of spirea (*Spiraea nipponica* Maxim. 'Snowmound') and azalea (*Rhododendron ×hybrida* 'Girard Pleasant White') (10 cm tall in 64-cm^3 containers) were potted in 3.8-L plastic containers filled with the 10 different substrates described previously. Osmocote Plus (15N–3.9P–10K; The Scotts Co.) was postplant top-dressed onto all containers at 3.5 and 5.25 kg·m^{-3}, respectively, for azalea and at 5.25 and 7.0 kg·m^{-3}, respectively, for spirea. Plants were grown on a gravel ground bed in a greenhouse in Blacksburg, VA, and overhead-irrigated (by hand) as needed to achieve an approximate 25% leaching fraction. Average day and night greenhouse air temperatures were 26 and 22 °C, respectively. Substrate solution was extracted using the PT method on 23 Apr., 22 May, 28 June, 29 July, and 7 Aug.; solutions were analyzed for pH and EC using a Hanna HI 9811 instrument. On 7 Aug.. GI was determined, and shoots were severed at the substrate surface, oven-dried, and weighed. A root

rating of 1 to 5 was given to each plant based on the density of roots on the outside of the root ball with 1 being the least amount of roots and 5 being the most.

The experimental design was completely randomized with 10 substrates and 10 replications per substrate for a total of 100 containers. Data were analyzed with SAS with substrate treatment means separated by Duncan's multiple range test ($\alpha = 0.05$) and differences in screen size analyzed by the least significant difference procedure.

Results and Discussion

Combining pine tree substrates of different particle sizes. Container capacity for 100% PTS-NS was 35.7% (Table 1). Increasing the proportion of finely ground PTS-4.76 in the more coarsely ground PTS-NS increased the CC from 40.4% for the 25%-PTS-4.76% to 52.6% for 100%-PTS-4.76. Container capacity for 100%-PTS-4.76 was lower than for PL but was higher than PB. Although small proportions of PTS-4.76 (50% or less) added to the coarse PTS-NS did not provide enough fine particles (less than 0.5 mm) to produce a PTS with the recommended CC of at least 45%, these data do indicate the potential of altering CC by combining different wood particle sizes (Table 1). Adding a more finely ground PTS produced with a 1.59-mm screen (containing 45% fines; data from previously unpublished work by these authors) rather than 100%-PTS-4.76 (14.9% fines; Table 1), would have increased the fraction of fine particles and the CC, most likely to equal that of PL and PB. In the case of this experiment, the incremental affect of adding PTS-4.76 to PTS-NS (2.3% fines) increased the percent fines from 5.0% in 25%-PTS-4.76% to 9.4% in 75%-PTS-4.76, the latter of which was comparable to PB (Table 1). The 14.9% fines in 100%-PTS-4.76 was equal to the percent found in PL. The ≈10% to 15% fines needed to obtain a desired CC in a 100% PTS in this study (compared with PL or PB) has also been noted in previous unpublished research by these authors that showed that a 100% PTS substrate with 15% fines corresponds to a CC of ≈45% to 50%, the lower end of the acceptable range for a container substrate. Thus, the percent fines of a PTS substrate should be at least 10% to 15% to achieve an adequate CC for the substrate and this benchmark can be attained with either sufficient grinding or by mixing various proportions of different particle size PTSs. Available water of PTS-4.76 at 100%, 75%, and 50% fractions was equal to the available water in PL, and available water (AW) in all PTSs was equal or higher that the AW percent of PB (Table 1).

Marigold shoot dry weight followed a similar trend as CC in response to increasing proportions of PTS-4.76 with maximum dry weight occurring at 100%-PTS-4.76 in which dry weight was equal to that for PL and PB (Table 1). Adding PTS-4.76 to PTS-NS at rates of 25% or more increased plant GI

Table 3. Physical properties of peat-lite (PL), pine bark (PB), and pine tree substrates (PTS) with various amendments.[z]

Screen size[y]	Substrate and amendment						
	PTS[x]	PTS-S[w]	PTS-PM[v]	PTS-HPB[u]	PTS-HPBS[t]	PL[s]	PB
Container capacity (% vol)[r]							
4.76 mm	50.5 c[q]	49.5 c	57.2 b	60.3 a	61.5 a	61.2 a	50.3 c
6.35 mm	44.2 d	46.5 d	51.7 c	56.5 b	54.9 b	61.2 a	50.3 c
9.35 mm	41.2 e	46.0 d	52.6 b	47.8 cd	52.0 b	61.2 a	50.3 bc
15.9 mm	38.1 d	41.6 d	53.1 b	50.3 b	52.3 b	61.2 a	50.3 bc
No screen	41.0 d	44.0 d	54.3 b	48.6 c	49.4 c	61.2 a	50.3 bc
Significance[p]	NS	NS	NS	NS	L*	—	—
	Q***	Q***	NS	Q**	Q**	—	—
P values[o]	Screen size (S) = ≤ 0.0001; Amendment (A) = ≤ 0.0001; S*A = ≤ 0.0001						
Air space (% vol)[n]							
4.76 mm	36.5 a	33.9 ab	30.9 b	24.9 c	19.3 d	17.6 d	24.8 c
6.35 mm	42.0 a	37.0 ab	35.8 bc	30.5 cd	25.5 d	17.6 e	24.8 d
9.35 mm	43.2 a	36.5 abc	34.4 bc	38.5 ab	29.5 cd	17.6 e	24.8 ed
15.9 mm	48.2 a	39.0 b	34.1 b	35.5 b	26.5 c	17.6 d	24.8 c
No screen	43.5 a	34.9 b	32.8 b	38.0 b	32.6 b	17.6 d	24.8 c
Significance	NS	NS	NS	NS	L*	—	—
	Q*	Q*	NS	Q*	Q**	—	—
P values	Screen size (S) = ≤ 0.0001; Amendment (A) = ≤ 0.0001; S*A = 0.0007						
Total porosity (% vol)[m]							
4.76 mm	86.9 ab	83.4 abc	88.1 a	85.2 abc	79.8 bcd	78.8 bc	75.1 d
6.35 mm	86.2 a	83.5 ab	87.5 a	87.0 a	80.4 abc	78.8 bc	75.1 c
9.35 mm	84.3 ab	82.6 ab	87.0 a	86.3 a	81.5 ab	78.8 ab	75.1 b
15.9 mm	86.2 ab	80.6 abc	87.3 a	85.8 ab	78.8 bc	78.8 bc	75.1 c
No screen	84.5 ab	78.9 bc	87.1 a	86.6 a	82.0 abc	78.8 bc	75.1 c
Significance	NS	L*	NS	NS	NS	—	—
	NS	Q*	NS	NS	NS	—	—
P values	Screen size (S) = 0.6766; Amendment (A) = ≤ 0.0001; S*A = 0.8199						
Bulk density (g·cm^{-3})[l]							
4.76 mm	0.15 c	0.24 ab	0.15 c	0.16 c	0.29 a	0.14 c	0.22 b
6.35 mm	0.16 c	0.25 ab	0.15 c	0.16 c	0.26 a	0.14 c	0.22 b
9.35 mm	0.16 c	0.26 a	0.15 c	0.15 c	0.27 a	0.14 c	0.22 b
15.9 mm	0.17 c	0.26 a	0.15 cd	0.18 c	0.26 a	0.14 d	0.22 b
No screen	0.17 c	0.27 a	0.17 c	0.18 c	0.29 a	0.14 d	0.22 b
Significance	L**	L*	L***	L*	NS	—	—
	Q***	Q***	Q***	Q**	Q**	—	—
P values	Screen size (S) ≤ 0.0001; Amendment (A) ≤ 0.0001; S*A ≤ 0.0001						

[z]Physical properties data were collected from three samples per substrate and represented as means. Analysis performed using the North Carolina State University Porometer method (Fonteno et al., 1995).
[y]Size of hammermill screens used to produce PTS.
[x]PTS produced from 15-year-old loblolly pine trees that were harvested at ground level, delimbed, chipped, and hammer-milled.
[w]PTS-S produced by amending PTS with 10% sand (9:1 ratio).
[v]PTS-PM produced by amending (mixed after grinding) PTS with 25% peatmoss (3:1 ratio).
[u]PTS-HPB produced by grinding fresh pine wood chips with 25% aged PB (3:1 ratio) in a hammermill.
[t]PTS-HPBS produced by amending 10% sand (9:1 ratio) to PTS-HPB.
[s]PL composed of 80% peatmoss/20% perlite (v/v).
[r]Container capacity is (wet weight – oven dry weight) ÷ volume of the sample.
[q]Means separated within row by Duncan's multiple range test ($P ≤ 0.05$) (n = 8). Means followed by the same letter are not significantly different.
[p]L = linear; Q = quadratic response for concentration at *, **, or ***.
[o]NS (nonsignificant) or significant at *$P ≤ 0.05$, **0.01, or ***0.001.
[n]Air space is the volume of water drained from the sample ÷ volume of the sample.
[m]Total porosity is equal to container capacity + air space.
[l]Bulk density after forced-air drying at 105 °C for 48 h.

values; these values were the same or higher than for GI values of PL- and PB-grown plants. Root ratings were higher in PTS treatments compared with PL or PB (except for 75%-PTS-4.76), likely reflective of the generally higher percent AS in PTS than that in PL and PB. Substrate solution pH increased as the percent of PTS-NS increased (Table 1). Substrate solution EC was higher in PL than the other substrates, a result that has been noted in other studies (Jackson et al., 2008b).

Pine tree substrate with various amendments. The particle size distribution in the formulated substrates was influenced by the interaction of the four amendments ($P ≤ 0.0001$ for all particle texture groups; Table 2). Percent fines decreased as the hammermill screen size increased for the five PTSs. Percent fines increased when peatmoss was mixed with PTS (PTS-PM) and when 25% PB was hammered with PTS (PTS-HPB) compared with PTS alone at all screen sizes. Adding sand to the PTSs showed a dramatic increase in fines compared with adding peatmoss or PB alone. This is a result of the high content of fine particles in the sand (93.2%), the reason for its inherently high BD compared with PTS, PL, or PB. Container capacity increased as screen size

decreased except for PTS-PM in which there was no change (Table 3). Amending PTSs with sand did not generally increase CC. Container capacity generally increased when 100% PTS was amended with 25% peat (PTS-PM) or hammered with 25% PB (PTS-HPB) compared with that of 100% PB. Container capacity for PTS-HPB or PB plus 10% sand (PTS-HPBS) produced with a 4.76-mm screen was at least 60% and was the same as the CC of PL. Container capacity for all PTSs amended with peatmoss, sand, or hammered with PB was within the recommended range of 45% to 65% CC for container substrates (Yeager et al., 2007) with the exception of PTS-NS and 15.9-mm PTS-S, which were slightly below the lower range (Table 3); 4.76-mm PTS was within the recommended range without any amendments as a result of its finer particle size. Treatments with acceptable CC (Table 3) also contained 15% or more fine particles (Table 2).

Air space decreased as screen size decreased [the inverse of the influence of screen size on CC (Table 3)] as a result of increased fines (Table 2), except for PTS-PM, which did not change, which was also the case with CC (Table 3). Similar to these results in PTS, the reduction of container substrate AS by the addition of fines (less than 0.5 mm) from PB or peatmoss in a PB (other coarse) substrate is well documented (Handreck, 1983). Air space also generally decreased with the addition of amendments (PTS versus amended substrates). In most cases, AS was considerably higher in PTS treatments than in PL or PB with the exception of PTS-HPBS for most screen sizes, and the AS was higher than the recommended range of 10% to 30% for container substrates. However, a higher than recommended AS may be acceptable if CC is in the proper range, which was the case for PTS-PM or PTS-HPB treatments. Total porosity was generally higher for PTS than for PB as a result of the higher AS for all screen sizes of PTS (Table 3). Amending PTS with sand (PTS-S) and PTS-HPB with sand (PTS-HPBS) resulted in the highest BD (Table 3). The increase in BD as a result of sand amendment has been documented in a 100% PB substrate (Brown and Pokorny, 1975; Pokorny and Henny, 1984a). The BD of unamended PTS as well as PTS-PM or PTS-HPB was similar to PL and lower than PB.

Reflective of the substrate CC, marigold shoot dry weight increased as screen size decreased regardless of PTS amendment (Table 4). Amending PTS with peatmoss, PTS-HPB, and PTS-HPBS with 4.76 mm PTS resulted in shoot dry weight equal or better than those grown in PL and PB. Shoot growth in 6.35 mm PTS-HPBS was equal to PL and PB; 6.35 mm PTS-HPB resulted in growth equal to PB but not PL. Marigold shoot dry weight for all other treatments was less than those for PL and PB. Growth index of plants decreased with increasing screen size in all treatments with the exception of PTS-PM, which corresponds to the result that CC was not altered by screen size in the PTS-PM substrates (Table 4). The PTS-PM, PTS-HPB,

Table 4. Plant growth of marigold grown in peat-lite (PL), pine bark (PB), and pine tree substrates (PTS) with various amendments for 4 weeks in 2008.

Screen size[t]	PTS[z]	PTS-S[y]	PTS-PM[x]	PTS-HPB[w]	PTS-HPBS[v]	PL[u]	PB
			Shoot dry wt (g)				
4.76 mm	6.5 d[s]	7.1 c	7.9 b	8.2 b	8.9 a	8.3 b	8.1 b
6.35 mm	5.8 e	6.6 d	7.4 c	7.6 bc	8.0 abc	8.3 a	8.1 ab
9.35 mm	5.6 e	6.5 d	7.4 bc	7.0 cd	7.6 abc	8.3 a	8.1 ab
15.9 mm	3.6 d	5.1 c	6.8 b	5.6 c	6.9 b	8.3 a	8.1 a
No screen	3.8 e	4.9 d	6.4 b	5.1 d	5.7 c	8.3 a	8.1 a
Significance[r]	L**	L***	L**	L***	L***	—	—
	Q***	Q***	Q***	Q***	Q***	—	—
P values[q]	Screen size (S) = ≤ 0.0001; Amendment (A) = ≤ 0.0001; S*A = 0.0002						
			Growth index (cm)[p]				
4.76 mm	30.3 c	31.2 abc	31.4 abc	32.7 a	32.1 ab	30.7 bc	31.2 bc
6.35 mm	30.2 b	30.7 ab	31.2 ab	32.1 a	31.4 ab	30.7 ab	31.2 ab
9.35 mm	28.7 d	29.8 cd	31.3 ab	32.4 a	31.1 b	30.7 bc	31.2 ab
15.9 mm	26.2 c	28.8 b	30.4 a	30.1 ab	30.8 a	30.7 a	31.2 a
No screen	27.0 c	29.1 c	30.3 ab	29.6 bc	30.2 abc	30.7 ab	31.2 a
Significance	NS	NS	NS	L***	L*	—	—
	Q***	Q***	NS	Q***	Q*	—	—
P values	Screen size (S) = ≤ 0.0001; Amendment (A) = ≤ 0.0001; S*A = 0.0064						
			Root rating[o]				
4.76 mm	2.2 b	3.0 a	2.2 b	2.0 b	2.7 a	1.0 c	1.2 c
6.35 mm	2.3 b	2.8 a	2.3 b	2.0 b	2.2 b	1.0 c	1.2 c
9.35 mm	2.7 ab	3.0 a	2.2 c	2.3 bc	2.2 c	1.0 d	1.2 d
15.9 mm	2.7 ab	3.0 a	2.2 c	2.3 bc	2.2 c	1.0 d	1.2 d
No screen	1.8 b	2.8 a	2.2 b	1.8 b	2.3 b	1.0 c	1.2 c
Significance	NS	NS	NS	L*	NS	—	—
	NS	NS	NS	NS	NS	—	—
P values	Screen size (S) = 0.0884; Amendment (A) = ≤ 0.0001; S*A = 0.0009						

[z]PTS produced from 15-year-old loblolly pine trees that were harvested at ground level, delimbed, chipped, and hammermilled to pass through each of the listed screen sizes.
[y]PTS-S produced by amending PTS with 10% sand (9:1 ratio).
[x]PTS-PM produced by amending (mixed after grinding) PTS with 25% peatmoss (3:1 ratio).
[w]PTS-HPB produced by grinding fresh pine wood chips with 25% aged PB (3:1 ratio) in a hammermill.
[v]PTS-HPBS produced by amending 10% sand (9:1 ratio) to PTS-HPB.
[u]PL composed of 80% peatmoss/20% peat-lite (v/v).
[t]Size of hammermill screens used to produce PTS.
[s]Means separated within row by Duncan's multiple range test (P ≤ 0.05) (n = 8). Means followed by the same letter are not significantly different.
[r]L = linear; Q = quadratic response for concentration at *, **, or ***.
[q]NS (nonsignificant) or significant at *P ≤ 0.05, **0.01, or ***0.001.
[p]Growth index [(height + widest width + perpendicular width) ÷ 3].
[o]Root rating of 1 to 3 assigned to the root balls of all plants = 1 being the least amount of roots and 5 being the most amount of roots.

and PTS-HPBS treatments (at all screen sizes) resulted in plants with GI equal to that of PL or PB. All plants, regardless of the substrate in which they were grown, were of high quality with no nutritional-related disorders (deficiency or toxicity). Fewer differences in GI compared with dry weight between plants grown in PTS and PL or PB has been noted with past experiments (Fain et al., 2008b; Jackson et al., 2008b). Root rating was unaffected by screen size except that PTS-HPB produced with NS was lower than for the other screen sizes (Table 4), but root ratings were higher for all PTSs than for PL and PB, especially for PTS-S. The generally higher root ratings for plants grown in PTS compared with plants grown in PL and PB could be a result of the higher AS in the PTSs (Table 3). However, because there was not a relationship between increasing AS as screen size increased, the increased root ratings for PTS may have been a result of the lower EC (nutrient levels; Table 5) with the PTS treatments compared with PL, because root growth is known to be more prolific under lower nutrition conditions rel-ative to shoot growth as shown by Niemiera and Wright (1982).

As a result of similar pH and EC values for the three PT dates (Weeks 2, 3, and 4 after treatment start), data were averaged over time (Table 5). pH values of the PTS treatments increased with increasing screen size and were higher for the PTSs compared with PL or PB except for 4.76 and 6.35 mm PTSs either unamended or amended with peatmoss or sand, in which case pH was equal to that of PL and higher than PB (Table 5). EC in PTSs decreased with increasing screen size and was always lower than the EC of PL. The EC of PTS produced with smaller screens was similar to that of PB and less than PB in PTSs produced with larger screens (Table 5). The latter result is most likely related to the higher nutrient retention capacity of a substrate with a relatively high fines content (Table 2) of a small screen-produced substrate compared with a substrate produced by a large screen-produced substrate.

These results confirm previous results that a 100% PTS produced with a 2.38-mm screen has an adequate amount of small particles and adequate CC for plant growth comparable to that in PL or PB (Jackson and Wright, 2009a; Saunders et al., 2006). Also, growth in coarser particle PTS produced with a 4.76- and 6.35-mm screen (Table 4) can be improved by incorporating sand, peat, or hammering wood chips and PB together, to equal growth of plants grown in PL or PB. The reason for this improvement in growth with decreasing screen size and with the additions of peat-moss and PB is most likely a result of the increased CC for these substrates (Table 3). However, because most of the amended substrates, even for PTS-NS, were within the acceptable CC range for container substrates, more specific irrigation management (watering each substrate individually based on loss of AW from the substrate) could have ame-liorated the growth difference between PTS-NS and PL or PB. Why sand additions to PTS and PTS-HPB increased growth is unclear because CCs for those substrates were un-affected by its additions (Table 3). Similar to these results, Niemiera et al. (1994) has shown that the CC of two PB:S [9:1 and 5:1 PB:S (v/v)] substrates were the same as for a 100% PB substrate although AS decreased as a result of the sand. Although amending substrates with sand does not increase CC, one possible explanation for the plant growth differences, as shown by Niemiera et al. (1994) in studies with PB, is that the sand significantly increased plant AW in the sub-strates. Another possible explanation is that the sand increased the water column and the accessibility of water by plant roots in the container by increasing capillary rise (in-creasing hydraulic conductivity) as a result of increased micropores in the upper region of the container. At the completion of the experiment, when plants were removed from the containers, PTS-S and PTS-HPBS treat-ments were observed to have sand particles well distributed down the entire (top to bottom) profile of the root ball, evidence that the sand did not settle or filter to the bottom of the pot during irrigations throughout the experimental period. Roots were observed growing in the top 5 cm of the PTS-S root ball in contrast to PTS and PTS-HPB substrates (that did not have sand), where no roots were visible in the top 5 cm. This observation explains the higher root ratings reported for PTS with sand additions previously discussed (Table 4). This observation led the authors to hypothesize that the sand simply retained water higher in the container, thus facilitating more root growth and water availability, potentially having the greatest positive im-plication during the first days after plugs were transplanted into the containers when water (and thereby fertilizer) would be held closer to the top of the containers and available for initial plant/plug growth. These observations and hypothesis are supported by Caron et al. (2005) whose research indicated increased subirrigation efficiency (as a result of in-creased capillary rise) in substrates when increased amounts of fines were added to a substrate composed primarily of bark. A third possibility may be that the sand incorporated

Table 5. pH and electrical conductivity (EC) of marigold grown in peat-lite (PL), pine bark (PB), and pine tree substrates (PTS) with various amendments.

Screen size[t]	Substrate and amendment						
	PTS[z]	PTS-S[y]	PTS-PM[x]	PTS-HPB[w]	PTS-HPBS[v]	PL[u]	PB
	pH						
4.76 mm	5.6 c[s]	5.6 c	5.9 bc	6.2 a	6.0 ab	5.7 c	5.3 d
6.35 mm	5.8 ab	5.8 ab	5.7 ab	6.0 a	6.0 a	5.7 b	5.3 c
9.35 mm	6.1 a	5.9 bc	5.8 b	6.1 a	6.1 ab	5.7 cd	5.3 d
15.9 mm	6.4 a	6.3 a	6.0 b	6.2 a	6.2 a	5.7 c	5.3 d
No screen	6.5 a	6.4 ab	6.2 b	6.5 a	6.4 a	5.7 c	5.3 d
Significance[r]	L**	L**	L***	L***	L***	—	—
	Q***	Q***	Q***	Q***	Q***	—	—
P values[q]	Screen size (S) = ≤ 0.0001; Amendment (A) = ≤ 0.0001; S*A = 0.0043						
	EC (dS·m⁻¹)[p]						
4.76 mm	1.80 b	1.82 b	1.85 b	1.62 b	1.62 b	2.43 a	1.79 b
6.35 mm	1.62 b	1.73 b	1.78 b	1.75 b	1.74 b	2.43 a	1.79 b
9.35 mm	1.50 c	1.56 bc	1.83 b	1.67 bc	1.82 b	2.43 a	1.79 bc
15.9 mm	1.39 c	1.40 c	1.53 bc	1.35 c	1.37 c	2.43 a	1.79 b
No screen	1.30 c	1.29 c	1.49 c	1.26 c	1.28 c	2.43 a	1.79 b
Significance	L***	L***	L**	L***	L***	—	—
	Q***	Q***	Q***	Q***	Q***	—	—
P values	Screen size (S) = ≤ 0.0001; Amendment (A) = 0.0006; S*A = 0.1024						

[z]PTS produced from 15-year-old loblolly pine trees that were harvested at ground level, delimbed, chipped, and hammermilled.
[y]PTS-S produced by amending PTS with 10% sand (9:1 ratio).
[x]PTS-PM produced by amending (mixed after grinding) PTS with 25% peatmoss (3:1 ratio).
[w]PTS-HPB produced by grinding fresh pine wood chips with 25% aged PB (3:1 ratio) in a hammermill.
[v]PTS-HPBS produced by amending 10% sand (9:1 ratio) to PTS-HPB.
[u]PL composed of 80% peatmoss/20% peat-lite (v/v).
[t]Size of hammermill screens used to produce PTS.
[s]Means separated within row by Duncan's multiple range test ($P \leq 0.05$) (n = 8). Means followed by the same letter are not significantly different.
[r]L= linear; Q = quadratic response for concentration at *, **, or ***.
[q]NS (nonsignificant) or significant at *$P \leq 0.05$, **0.01, or ***0.001, respectively.
[p]1dS·m⁻¹ = 1 mmho/cm.

Table 6. Dry shoot weight (g) and growth index (GI; cm)[z] of *Rhododendron ×hybrida* 'Girard's Pleasant White' and *Spiraea nipponica* 'Snowmound' grown in pine bark (PB) and pine tree substrates (PTS) with various amendments.

Screen size[t]	Substrate and amendment					
	PTS[y]	PTS-S[x]	PTS-HPB[w]	PTS-HPBS[v]	PB	PB-S[u]
	Azalea dry shoot wt					
9.35 mm	32.0 ab[s]	35.0 ab	37.0 a	34.0 ab	31.0 b	33.0 ab
No screen	25.0 c	31.0 ab	26.0 bc	32.0 a	31.0 ab	33.0 a
LSD[r]	*	NS	*	NS	—	—
	Azalea growth index					
9.35 mm	28.0 a	28.0 a	29.0 a	27.0 a	30.0 a	29.0 a
No screen	25.0 c	26.0 bc	25.0 bc	28.0 ab	30.0 a	29.0 a
LSD	*	NS	*	NS	—	—
	Spirea dry shoot weight					
9.35 mm	51.0 b	50.0 b	58.0 a	60.0 a	55.0 ab	59.0 a
No screen	39.0 d	45.0 c	51.0 b	56.0 ab	55.0 ab	59.0 a
LSD	*	NS	*	NS	—	—
	Spirea growth index					
9.35 mm	53.0 b	53.0 b	58.0 ab	61.0 a	59.0 a	59.0 a
No screen	52.0 c	53.0 bc	55.0 ab	59.0 a	59.0 a	59.0 a
LSD	NS	NS	NS	NS	—	—
	Spirea root rating					
9.35 mm	4.0 a	5.0 a	3.0 b	3.0 b	2.0 c	2.0 c
No screen	4.0 ab	4.0 a	3.0 ab	3.0 b	2.0 c	2.0 c
LSD	NS	NS	NS	NS	—	—

[z]Growth index [(height + widest width + perpendicular width) ÷ 3].
[y]PTS produced from 15-year-old loblolly pine trees that were harvested at ground level, delimbed, chipped, and hammermilled.
[x]PTS-S produced by amending PTS with 10% sand (9:1 ratio).
[w]PTS-HPB produced by grinding fresh pine wood chips with 25% aged PB (3:1 ratio) in a hammermill.
[v]PTS-HPBS produced by amending 10% sand (9:1 ratio) to PTS-HPB.
[u]PB-S produced by amending PB with 10% sand (9:1 ratio).
[t]Size of hammermill screens used to produce PTS.
[s]Means separated within row by Duncan's multiple range test ($P \leq 0.05$) (n = 8). Means followed by the same letter are not significantly different.
[r]Means separated within columns (between 9.35-mm and no screen) by least significant difference (LSD) at $P \leq 0.05$.
NS = nonsignificant.

in these treatments (PTS-S and PTS-HPBS) is providing additional silicon (Si) to the substrate solution, which can improve plant growth. Research on the role of Si in improving plant growth has gained much interest in recent years (Chen et al., 2000; Kamenidou et al., 2008) and some initial unpublished results by one of these authors (Brian Jackson) has shown that sand does significantly increase soluble substrate solution Si concentrations for container-grown plants compared with Si levels in substrates not amended with sand.

Azalea and spirea growth in amended pine tree substrate. There were minor substrate differences for azalea shoot weight for the 9.35-mm PTS treatment; dry weight for PTS-HPB was higher than 100% PB (Table 6). The reason that plant growth for this treatment was higher than azalea plants grown in PB is not understood because plant growth in PB is normally equal to or higher than plant growth in PTS. Adding sand to the PTS-NS increased azalea shoot dry weight over PTS-NS alone, and adding sand to PTS-HPB resulted in growth equal to PB and PB-S (Table 6). Azalea growth indices were the same for all 9.35-mm PTS treatments but shoot dry weight in PTS-NS hammered with PB plus sand was larger than PTS-NS alone and equal to shoot dry weight of plants grown in PB and PL. Shoot dry weight and GI were higher for 9.35-mm PTS than PTS-NS, but adding sand resulted in no growth differences between these substrates. Adding sand to PB did not increase azalea shoot growth (Table 6).

For spirea, treatment responses were similar to those of azaleas. For 9.35-mm PTS and PTS-NS, hammering the PTS with PB increased growth over unamended PTS resulting in dry weight equal to PB (Table 6). Adding sand to PTS-HPB (PTS-HPBS) resulted in dry weight equal to both PB and PB-S. Growth index of both 9.35-mm PTS and PTS-NS were increased by hammering with PB (PTS-HPB) and hammering with PB plus sand (PTS-HPBS; Table 6). Adding sand did not increase GI when comparing PTS with PTS-S, PTS-HPB with PTS-HPBS, and PB with PB-S. The pH of PTS-HPB and PTS-HPBS were higher than PB or PL for azalea and spirea (Table 7). All pHs observed in this study were within a suitable range for the production of most nursery crops. However, because PTS is weakly buffered compared with peatmoss or PB, withholding limestone additions to PTS and using acidifying fertilizers could reduce pH to an acceptable level (Jackson et al., 2009b).

Conclusion

The studies mentioned show that amending coarsely ground PTS with finer particle PTS or with other materials (peatmoss and aged PB) can result in a substrate with comparable physical properties (CC and AS) and plant growth as with 100% PB and PL substrates (Table 3). Other similar materials (composts, coconut coir, pine bark fines,

Table 7. Average electrical conductivity (EC) and pH levels of substrate solution during the growth of *Rhododendron ×hybrida* 'Girard's Pleasant White' and *Spiraea nipponica* 'Snowmound' grown in pine bark (PB) and pine tree substrates (PTS) with various amendments.

Screen size[u]	Substrate and amendment					
	PTS[z]	PTS-S[y]	PTS-HPB[x]	PTS-HPBS[w]	PB	PB-S[v]
	Azalea pH					
9.35 mm	5.8 b[t]	6.0 b	6.3 a	6.4 a	5.9 b	5.9 b
No screen	6.1 abc	6.0 abc	6.3 a	6.3 ab	5.9 c	5.9 bc
LSD[s]	NS	NS	NS	NS	—	—
	Azalea EC ($dS \cdot m^{-1}$)[q]					
9.35 mm	0.8 a	0.9 a	0.8 a	0.9 a	0.9 a	0.8 a
No screen	1.0 a	0.9 a	0.8 a	0.9 a	0.9 a	0.8 a
LSD	NS	NS	NS	NS	—	—
	Spirea pH					
9.35 mm	5.8 bc	5.7 bc	6.0 ab	6.2 a	5.4 d	5.5 cd
No screen	5.8 b	5.8 b	6.2 a	6.2 a	5.4 c	5.5 cd
LSD	NS	NS	NS	NS	—	—
	Spirea EC ($dS \cdot m^{-1}$)					
9.35 mm	0.9 a	1.2 a	1.3 a	1.2 a	1.2 a	1.2 a
No screen	1.0 a	1.0 a	0.9 a	1.0 a	1.2 a	1.2 a
LSD	NS	NS	NS	NS	—	—

[z]PTS produced from 15-year-old loblolly pine trees that were harvested at ground level, delimbed, chipped, and hammermilled.
[y]PTS-S produced by amending PTS with 10% sand (9:1 ratio).
[x]PTS-HPB produced by grinding fresh pine wood chips with 25% aged PB (3:1 ratio) in a hammermill.
[w]PTS-HPBS produced by amending 10% sand (9:1 ratio) to PTS-HPB.
[v]PB-S produced by amending PB with 10% sand (9:1 ratio).
[u]Size of hammermill screens used to produce PTS.
[t]Means separated within row by Duncan's multiple range test ($P \leq 0.05$) (n = 8). Means followed by the same letter are not significantly different.
[s]Means separated within columns (between 9.35-mm and no screen) by least significant difference (LSD) at $P \leq 0.05$.
NS = nonsignificant.

and so on) would also likely provide the fines needed in PTS for increased water retention. These other amendments/materials (either organic or inorganic) could potentially be waste/byproduct materials that currently have limited or no use or market for sale, thereby creating an avenue of use/disposal. Depending on the amendment used in PTS construction to supply the fines required, these materials could also possibly improve the CEC of PTS and improve the pH-buffering capacity of PTS, which has been shown to be very low compared with PL (Jackson et al., 2009b). An additional benefit of amendments (fines) to PTS could be improvement of the hydrophysical properties such as hydraulic conductivity, which has been shown to be much higher in PTS than PL (Jackson and Wright, 2009a). The improvement of PTS hydrophysical properties (rewettability, infiltration, hydraulic conductivity, and so on) can be substantially important in more accurately managing irrigation during cultivation.

This research indicates that there needs to be sufficient fine particles in any amendment to achieve at least 10% to 15% fines in the resulting substrate for an acceptable CC. Although unaffecting CC, the addition of sand to PTS did improve plant growth, therefore justifying its use as a PTS amendment. The use of sand as an amendment to PTS would likely be used in the construction of PTSs used in nursery crop production because sand can interfere with greenhouse potting machinery. For the construction of PTSs as greenhouse substrates, organic ma-

terials (composts, peatmoss, and so on) would be more likely added to supply the fines needed to improve physical properties. Construction of wood substrates from other tree species such as red cedar (*Juniperus virginiana* L.), which has been most recently reported by Griffin (2009), could also use and benefit from the methods discussed in this article for substrate construction. Previous research reported in 2006 (Rau et al., 2006) has shown that hardwood tree species were unsuitable for use as a container substrate as a result of how quickly they decompose and shrink during crop production (a result of the lower lignin content in hardwoods compared with pines) and as a result of higher amounts of phytotoxins in different wood species. The substrates used in those studies were processed through a 4.76-mm hammermill screen, which, as shown in results in this article, produces a high percentage of small wood particles. These smaller particles would have had accelerated decomposition in containers (compared with larger wood particles), which could have been one explanation for the negative effect on plant growth that was observed. Based on methods of substrate construction (grinding wood to have large particles and amending with other materials for the fine particles) discussed in this work, it is conceivable that hardwood species could be viable for use as a substrate component because the wood particles would be larger, decreasing their decomposition rate.

In addition to the advantages discussed, there may be other advantages to amending

coarsely ground PTS with finer ground components. A more coarsely ground PTS would be less expensive to manufacture. Preliminary unpublished studies have shown that the output of PTS-NS from the 25-hp hammermill used in these studies would be ≈76 kg/hp/h compared with only 16 kg/hp/h for a hammermill fitted with a 4.76-mm screen. The output would change with the type and power of hammermill used for wood processing. The lower output for producing a smaller particle PTS (e.g., PTS-4.76) would increase inputs such as labor, energy cost for grinding, and require a more expensive hammermill designed to move material (coarse pine chips) through a smaller screen. Whether these savings would offset the cost of adding 25% peatmoss or aged PB to PTS would need to be carefully evaluated. One factor that has been observed to affect PTS production rates is the moisture content (%) of the wood at the time of processing/ grinding. The moisture content of freshly harvested pine trees is normally between 50% to 55% based on unpublished observations of these authors (Brian Jackson and Robert Wright), and the amount of moisture in wood chips directly influences the processing rate (reduction of particle size in a hammermill) with higher moisture increasing processing/grinding time and decreasing PTS output from the hammermill. As a result of the longer grinding time of moist wood chips (greater than 50% moisture), the amount of fines has also been observed by these authors to increase compared with the amount of fines produced from drier wood chips (less than 30% moisture). Different moisture contents of pine wood chips at the time of grinding is likely the reason why PTS-4.76 was shown to have different percentages of fine particles; 14.9% fines (Table 1), 17.5% fines (Table 2), and even 19.5% fines have been reported by Jackson et al. (2009a). A second factor to be considered when processing wood for use as a container substrate is the type of equipment used for processing (grinding) wood chips. Hammermills appear to be the best choice for this task, but mills can vary considerably between brands (horsepower, air handling devices, motor rpm, hammer tip speed), which will affect the amount of wood that can be processed. These and possibly other factors that could influence PTS construction/processing should be considered and more thoroughly investigated. Regardless of the effect that pregrinding wood moisture will play on the processing of wood, or the equipment used for processing wood into a substrate, the results presented in this article illustrate the feasibility and success in constructing a wood substrate with adequate physical properties and plant growth compared with traditional substrates.

Another important advantage of manufacturing a more coarsely ground PTS may be that the extra fertilizer required for PTS compared with PB or peatmoss (Jackson et al., 2008a; Wright et al., 2008a) will be

reduced because other work by these authors has shown that additions of peatmoss and PB to PTS reduce substrate microbial activity and N immobilization (Jackson and Wright, 2009c). The work by Jackson and Wright (2009c) also showed that microbial activity and N immobilization in PTS is reduced when PTS particle size increases. As a result of recent industry trends for the production of large woody plants in large containers (greater than 45 L for over 2 years), production of PTS composed of larger particles (PTS-NS) would decay less rapidly and facilitate substrate stability over these long production periods. The exact extent to which all these factors influence cost of production is not totally understood but with further investigations will become more apparent.

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