Strategies for Developing Sustainable Substrates in Nursery Crop Production

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Abstract

A comprehensive literature search of industrial and agricultural by-products to replace or extend existing soilless substrate components would produce a seemingly endless list of materials from "garbage" to a plethora of manure-based composts that have been tested both in the laboratory and in crop response studies throughout the world. Many of these alternatives have shown promise, but limiting factors for integration and use of the alternatives substrate components continue to include: regional or national availability; transport costs; handling costs; lack of a uniform and consistent product; guidelines for preparation and use of materials or impact on current crop production practices. If a product can overcome the above limitations, then researchers are tasked with documenting substrate physical or chemical characteristics. The objective in all studies is to maintain or increase growth of nursery crops and to extend the longevity and acceptable physical properties for long-term woody ornamental crops. Proof of results is determined using laboratory analyses and crop growth studies. Physiochemical properties are monitored over days, weeks, and months to ensure stability. Particle size distribution and varying ratios of substrate components are manipulated to achieve optimal air filled porosity and available water content. Soilless substrates are amended with lime, sulfur and nutrients or blended with other substrate components to provide optimal chemical characteristics. Additionally, substrates are evaluated under industry conditions to determine impact on water, nutrient and pest management to better understand obstacles to commercial adoption.

INTRODUCTION

Container-grown plant substrate components have been the focus of much research since the 1950's when containerized nursery and greenhouse crop production began on a large scale (Davidson et al., 2000). Mined soil, Canadian *Sphagnum* peat and sand were used to produce containerized crops in the United States during the mid 20th century as growers began to readily produce plants in above-ground containers (Lunt and Kohl Jr., 1956). Simultaneously, drip-irrigation and liquid fertilizer became available to growers. These new technologies coupled with container production allowed growers to produce, harvest and transport plants with greater ease, thus resulting in a more profitable business (Davidson et al., 2000). However, this newly adopted system was not without issue. The use of field soil resulted in unfavorable physical properties for floriculture greenhouse crops and container-grown nursery crop production. It also harbored numerous pathogens requiring sterilization and additional handling (Scott and Bearce, 1972).

The University of California (UC) System introduced organic components that included bark, peat and wood shavings, and resulted in a shift in crop production practices (Baker, 1957). Growers began incorporating additional components into containerized soil to increase water infiltration, decrease disease incidence and create a lighter grower system for ease of shipping. Soon thereafter researchers and growers began to experiment with incorporating wood shavings from deciduous and coniferous tress species with mixed success (Furata, 1974). Redwood (*Sequoia sempervirens* Endl.) shavings were successfully adopted and remain today as a component of soilless substrates in the Southwestern United States. Concurrently, researchers began to investigate bark in the Southeastern and Northwestern United States. Bark was successfully proven as beneficial amendment to soil and peat based container substrates, however there was opposition and disbelief that it could be used as the major or only component in soilless substrate. The southeastern nursery industry adopted pine (*Pinus taeda* L.) bark and relentless pursuit of research and outreach by Pokorney in the 1970's. At the same time, Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] bark was being adopted as the primary component in the Pacific Northwest.

In the past three decades, bark and peat have been considered the ideal soilless substrate component for short and long term horticultural crops in the United States. Both peat and bark are stable over time remaining well drained, but retain adequate available water for crop growth when irrigated regularly. Peat and bark are both acidic with little buffering capacity. Although both require a lime or dolomite amendment to raise and maintain a pH of 5.0 to 6.5, peat usually requires a higher amendment rate than bark. Water and nutrients are added regularly to produce a salable crop. Inorganic components have been added to peat and bark to increase stability of physical properties over time and increase the bulk density of the substrate to ensure the container and plant remain upright. Bark became scarce because of unprecedented use in as horticultural product and alternative energy source at the apex of the green economic boom in the United States at the turn of the 21st century. Concurrently, peat was undergoing greater scrutiny in England and the United States. Recently concern has been escalating over the cost and future availability of peat moss and bark for the horticultural industry. These concerns are related in part to energy costs and the sustainability of energy resources in the world today. The concerns are slightly different for the two components.

Bark is a byproduct of the timber industry. Pine bark from southern forests is utilized in the horticultural industry from the Florida, to the east coast and the mid-west. While Douglas fir bark is the primary nursery substrate for the Pacific North West. Bark, once a waste product that represented a significant disposal problem, is now considered a significant part of the future supply chain of renewable energy. Many industries that utilize wood fiber for producing consumer products are utilizing pine bark as a boiler fuel source. The projected supply of bark for horticultural use is particularly precarious. A study by Lu et al. (2006) showed a consistent decline in the availability (and subsequent rise in price) of pine bark due to reduced domestic forestry production, increased importation of logs (no bark), increased in-field harvesting (leaving bark on the forest floor rather than at the mill), and use of pine bark as a source of fuel. Current forest product inventory assessments show that less than 5% of the bark supply is available for horticultural use. Since this study, new industries have arisen in the United States that have begun producing alternative energy products for Europe. These products are wood fuel pellets that are made from wood biomass produced from forestry products. While the bark is not used in the wood pellets the main energy need for the facilities producing the pellets is achieved through the combustion of the pine bark removed from the logs. The current production process of wood fuel pellet manufacturing eliminates bark from the supply chain and is therefore no longer available to horticultural producers. In addition, the quantity of timber harvested in the United States has decreased since 1986.

We believe identifying alternative components that can be used as bark alternatives or as supplement to extend bark supplies is a critical to the success of the United States nursery and greenhouse industry. Within the past 5-years academic institutions and commercial soilless substrate suppliers have begun to allocate resources to the research of bark and peat alternatives. Peat and bark alternatives have been predominately wood-based alternatives from forestry and related by-products such as culled or unsalable whole trees or slash and residual that remain after harvesting. Recently, there has been a shift from perennial forestry generated biomass to annual crops and their byproducts. This includes commodity crops such as corn or biofuel crops such as grasses that yield large amounts of biomass annually. This paper will review the criteria used in selecting suitable peat and bark alternatives, the process of evaluating an alternative substrate and a review of current research being conducted in the United States.

SELECTION AND EVALUATION CRITERIA

The problem the nursery and greenhouse industry faces is that there is an increasing carbon shortage in the United States that is resulting in a decrease of available biomass for use in horticultural crop production. Simultaneously, US horticultural producers are trying to meet consumer demands for more sustainable production practices and products while trying to remain viable in a slow economy. This results in a need for low cost, locally available products that is viewed as sustainable and meets consumer traditional preferences of touch and appearance. In addition, US researchers agree that alternative soilless substrates must be able to replace up to or greater than 30% (by volume) of peat or bark used in conventional soilless substrate mixes. It is also preferred that the horticultural producer control the biomass used in the soilless substrate from production through processing to the end use. This allows the grower to ensure there are no competing uses and control quality and cost.

The first step in the process is to determine if the biomass to be used as a soilless substrate can be produced by the end user or if the grower will have to rely on regionally available forms of biomass. In most cases, individual nursery or greenhouse operations do not have the resources to produce and process their own biomass; therefore a regional biomass assessment needs to be performed. This entails interviewing local horticultural producers and identifying acceptable soilless substrate component alternatives within the region.

The next step in the selection process is to determine the crop and environment, greenhouse or nursery, in which you are considering to introduce an alternative soilless substrate component. The choice will dictate cropping time and the substrate component to be replaced, peat or bark. Next, regional availability of a biomass must be considered. When considering a biomass one must look for a product that is free of weeds, pathogens and residuals pesticides. The biomass must remain physically and chemically consistent over time. There should be no foreseen future competition for that product. One must consider if there are conventional methods of harvesting, handling, shipping, and processing the biomass and are these practices sustainable in regards to energy and water. Processing must yield reproducible, uniform product overtime regardless if used fresh or after being stored. After a biomass is identified and preliminary answers are determined to the previous questions, one must determine the cost of using the selected alternative substrate. If the preliminary economic analysis of using the biomass results in no loss or net economic gain then the biomass needs to undergo a thorough screening within a greenhouse and nursery environment.

The screening process begins with testing the material for phytotoxicity via a bioassay in which a seed is directly germinated on the selected alternative substrate or using solution from a water extract. If the alternative substrate is not phytotoxic or unacceptably reduce plant vigor, physical and chemical properties of the alternative substrate are determined at various dilutions using peat moss or bark. Initial physical properties include particle size, air space (AS), total porosity (TP), container capacity (CC), dry bulk density (D_b) (Fonteno and Bilderback, 1993) Researchers at Oregon have also included a wet bulk density measured at container capacity. This value is used to compare substrates in regards to transport costs and container stability during crop production. Chemical properties are commonly determined first by a saturated media extract (SME) or pour-through to measure pH and electrical conductivity (EC). The collected effluent is further analyzed by a regional laboratory for metals using inductively coupled plasma-optical emission spectroscopy. Selected substrate combinations are then evaluated for short-term crop production using floriculture or vegetable crops. This initial evaluation compares crop response in an alternative versus conventional substrate while providing insight into change in physical properties over a short duration and chemical properties over time as measured by the pour-through methods. Research using a short-term crop allows the researcher to evaluate the optimal rate (percent by volume) that yields a marketable crop within less or the same time as conventional practices. This short-term provides the foundation of research for floriculture crops or the preliminary research to begin long term projects using woody ornamental crops that may reside in a single container for 6 to 18 months. The optimal rate of alternative substrate incorporation may be refined for woody alternative crops, however regardless of cropping system researchers continually need research to improve or modify production practices to increase overall efficiency. This includes research on water management, fertility, pH, physical properties and environmental impact.

Lastly, research is needed to better understand consumer acceptance and if there will be any implications to a change in color or texture of the product and how these barriers can be overcome with branding and education. Researcher must also ensure post sale handling results in a thriving ornamental plant that can be used in the house or garden, respectively without additional care than currently provided to conventional ornamental crops.

Criteria Synopsis

- Crop and production environment
- Regional availability
- Processing and storage
- Cost and value-added

- Crop phytotoxicity
- Physiochemical properties
- Production practices and crop management
- Consumer acceptance
- Post-transplant success.

ALTERNATIVE SUBSTRATE CASE STUDIES

Pine Tree Substrates (PTS)

The use of freshly harvested and processed pine trees as a container substrate for greenhouse and nursery crop production is a relatively new concept. Construction of a pine tree substrate (PTS) for optimal physical properties is a primary focus of current research. Pine tree substrates can be produced from pine trees that are chipped and ground (with or without bark, limbs, needles, etc.) in a hammer mill, or from clean chip residual (CCR: approximately 40% pine wood, 50% bark, and 10% needles) which is produced from by-products of the pine tree harvesting process (Boyer et al., 2006; Fain et al., 2006). It has been shown that pine wood chips that are hammer-milled into a PTS with a particle size range and physical properties comparable to aged pine bark (PB) and peat-based substrates are acceptable for use as a container substrate (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., 2008; Jackson et al., 2008b; Wright et al., 2008) crops can be produced with similar quality to plants grown in peat moss or PB. Some advantages of PTS are: 1) PTS can be produced in close proximity to growers and substrate companies in the southeastern US 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 CC and air space AS can be 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 hammer mill. Producing PTS with a particle size fine enough to possess an adequate water holding capacity similar to peat moss or aged PB, is expensive as a result of costs associated with grinding (primarily energy costs). Another approach is to mix larger PTS particles with various proportions of fine PTS particles (<0.5-mm) which result in a PTS with adequate AW and AS.

Based upon the concept that PTS substrates could be suitable for long term production Jackson and Wright (2009) studied decomposition and changes in physical and chemical properties over time under outdoor conditions. Total porosity was higher in PTS (91.2%) and above the recommended range (50% to 85%; Yeager et al., 2007) at the beginning of the study (initial) compared with PB (83.2%; Table 1). Air space was higher in PTS (35.9%) and also above the recommended range (10% to 30%) at the beginning of the study than PB (26.4%), which was within the suggested range. Container capacity was equal in PB and PTS initially (56.8% and 55.3). Bulk density was lower in PTS than PB initially, and both were below the recommended range (0.19 to 0.70). Data for 70 WAP (Weeks After Potting) found that total porosity was unchanged in PB compared with the initial TP. Air space percentages were lower in PB at 70 WAP than initially, but percentages remained within the recommended range. Inversely, CC and BD of PB increased at 70 WAP. Container capacity increased at 70 WAP in PTS with and without plants and was equal to PB. Bulk density remained lower in all PTS treatments than PB but remained within the recommended range. Shrinkage after 70 weeks was highest in fallow PTS, but shrinkage in PTS that contained plants was equal to PB with plants (Table 1). Ultimately, substrate shrinkage in PTS would be a major concern if not for plant roots that apparently fill the voids caused by decomposition.

Douglas Fir Slash and Culled Christmas Trees

Oregon consistently ranks as one of top five nursery states within the United States selling 600 million dollars of nursery stock annually. Douglas fir bark is the prominent soilless substrate component in the Oregon; however regional scarcity and physico-chemical inconsistency continue to affect nursery crop producers. Douglas fir slash and culled Christmas trees (*Abies nordmanniana*, *Abies procera*) are abundant sources of biomass in the US Pacific Northwest that have been traditionally disposed of via burning. Approximately 15% to of the over 6 million Christmas trees planted annually will be disposed of during their multi-year production cycle. Concurrently, there are over 600,000 acres of managed Douglas fir timber in Western Oregon that yields an estimated 20,000 million board feet or more annually. Considerable amounts of unharvested forest residual or timber slash from the harvests is piled and burned. There is increasing regulation limiting the burning of biomass in Oregon, leaving both the Christmas tree and timber industry looking for alternative sources of biomass disposal. Therefore, the regional proximity of the biomass and the ties of forestry and Christmas tree industry to the ornamental nurseries make culled trees and timber slash a very promising alternative to Douglas fir bark.

Research has been conducted at Oregon State University North Willamette Research and Extension Center to investigate the use of hammer-milled culled Christmas trees and timber slash as a partial or total replacement for Douglas fir bark. Both sources of biomass were processed to most closely resemble particle size distribution and physical properties of the Douglas fir bark; however particle wettability and water holding capacity differ greatly impacting substrate available water content. Physical properties of both substrates are reported in Tables 2 and 3.

Conventional soilless substrate amendments (dolomite, micronutrients) and controlled released fertilizer were used. The addition of either alternative resulted in an increase in pH (Tables 2 and 3, however it is believed this could easily be overcome by a reduction in lime rate. Azalea x 'Coral Bells' was used an indictor crop to evaluate each alternative substrate (Table 4). Crop growth declined linearly with increasing percent of an alternative substrate regardless if Douglas fir slash or Christmas tree. It is hypothesized that this was primarily a result of N immobilization that was exacerbated by increased pH and preferential uptake of ammonium by ericaceous plants. Both Douglas fir slash and Christmas tree need additional research, however both show great promise as bark replacement in Oregon. Research is currently being conducted on pH, fertility and water management of both alternative substrates.

Commodity and Biofuel Crops

Within any particular region of the US nursery substrates may be quite different from one nursery to another. However, in the Eastern US most nursery potting substrates contain pine bark, in the Western US, Douglas Fir bark. A typical substrate in Ohio would be composed of 60 to 80% pine bark, 10 to 20% sphagnum peat moss, and 5 to 10% municipal solid waste (MSW) compost. Other components are added by various nurseries, generally in much smaller proportions than the aforementioned components. An approach to research for alternative components has been to start with a defined 'standard' substrate composed of 80% pine bark, 15% sphagnum peat moss, and 5% MSW compost. Identified alternative substrates are investigated to determine what percent of the pine bark can be replaced by alternative material while holding the sphagnum peat moss and MSW compost constant. Experiments conducted have examined switchgrass (*Panicum virgatum*) (Altland and Krause, 2009), miscanthus (*Miscanthus* ×*giganteus)* straw (Altland and Locke, 2011), wheat (*Triticum* sp.) straw (data unpublished), and bamboo (*Phyllostachys* spp.) (data unpublished). Results for each straw material have been similar in how they affect physical properties, substrate pH, and overall plant growth. In general, straw-based substrates need a small portion of the substrate to remain as pine bark. Components and ratios that have worked well with switchgrass, miscanthus, wheat straw, and bamboo substrates are: 60% straw material ground with 4.8 mm hammermill screen; 20% pine bark; 15% sphagnum peat moss and 5% municipal solid waste compost. Subsequent research has shown that addition of peat and MSW compost is critical to stabilizing pH and water relations in straw-based substrates (Altland and Krause, 2010).

Data previously reported by Altland and Locke (2011) in Table 2 show results from hibiscus (*H. moscheutos*) growing in substrates where the pine bark fraction has been replaced by ground miscanthus straw (MS). Five substrates were created that contained 15% sphagnum peatmoss, 5% municipal solid waste compost, and the remaining 80% consisted of one of the five following PB:MS ratios: 0:80, 20:60, 40:40, 60:20, and 80:0. Luna Red hibiscus (*Hibiscus moscheutos*) were grown in each substrate and evaluated for eight weeks in a greenhouse. Ground MS increased air space and decreased container capacity and bulk density as its concentration in the substrate increased. Additions of MS did not affect hibiscus chlorophyll content, and had negligible effects on hibiscus foliar nutrient levels. Increasing levels of MS caused a decrease in plant shoot dry weight, although growth reduction was most pronounced with 80% MS. Ground MS has potential to be a suitable substrate for nursery growers; however, some changes to management practices will be necessary.

Consumer and Agricultural Resources

Cotton is a major agronomic crop in N.C. and the Southeastern United States. In production of no-till cotton, stalks and residue remaining after harvest are very woody and do not easily decompose. This mulch may persist for several seasons and eventually the accumulation can interferes with planting and application of fertilizer and herbicides, Animal production agriculture remains a very important segment of the US economy and food supply. Poultry and hog industries struggle with maintaining environmentally safe animal waste handling practices. Poultry waste is often field applied as a crop fertilizer, but application frequency and rates are limited. Similarly, swine wastes have been traditionally managed by open air lagoons and spray-fields. As a result environmental concerns, finding other means to utilize animal waste resources would be welcomed. To date millions of dollars have been spent attempting to solve animal waste management problems. Utilizing animal wastes to compost agricultural crop residues provides a backyard accessible approach to composting large amounts of farm available carbon rich crop residues and an unwanted nitrogen source from animal wastes to create regionally available nursery substrate components. Combining cotton stalks and animal wastes into a composted substrate component is simple solution to a complex problem. The end product produces an odorless, dark, pine bark-like substrate. At first glance composted cotton stalks appear to be pine bark. Warren et al. (2009) reported research utilizing cotton stalks and swine waste. The experiments amended pine bark with four rates [0%, 15%, 30%, and 45% (by vol.)] of composted cotton stalks/swine waste (CCSW). No micronutrients or dolomitic limestone amendments were added to these substrates. For comparison to a common commercial substrate, 8 pine bark: 1 sand (by vol.) (PBS) was amended with 0.9 kg m^{-3} dolomitic limestone and 0.7 kg m^{-3} micronutrient fertilizer.

Total porosity, container capacity, available water, and unavailable water increased with increasing rate of CCSW (Table 5). In addition, all substrates amended with CCSW had greater total porosity and less available water compared to the control. In contrast, air space and bulk density decreased with increasing rate of CCSW. Air space was greater and bulk density was less in CCSW amended substrates compared to the control. The key to engineering substrates for optimal physical properties relies on maintaining a balance particularly between air space and water content. Air space is critical in substrates for root metabolism and growth; low air space reduces root adsorption capacities. Substrates with low available water retention may require frequent irrigation to avoid stomatal closure and wilting due to moisture stress.

A 20% to 30% air space is preferable for nursery size containers. Thus, the 0% CCSW at 33% AS (by vol.) was very high at 63 DAI and barely inside the range at 135 DAI. In contrast, pine bark: sand was on the low end of the range at both 63 and 135 DAI. Air space values for 15%, 30%, and 45% amended substrate fell between 0% CCSW and the control. Most organic based substrates including pine bark decrease in air space during production conditions with high irrigation application and fertilizer application. As air space decreases in substrates during a growing season, a reciprocal increase in container capacity usually occurs. Except for 45% CCSW which remain unchanged, these substrates increased 3% to 5% in container capacity from 63 to 135 DAI which was associated with the decline in AS. However, container capacity values remained within normal ranges. At 63 DAI, 0%, 15%, and 30% CCSW had lower available water compared to the control. At 135 DAI, all CCSW amended substrates had lower available water than the control. Bulk density decreased linearly with increasing rate of CCSW (Table 5). Changes in bulk density reflect the stability of substrate components. The bulk density of all CCSW amended substrate decreased 4% to 9% from 63 to 135 DAI indicating the particles were decomposing and reducing the volume of the substrate, whereas the pine bark: sand substrate changes very little from 63 to 135 DAI. CCSW when used as a bark amendment has the potential to stretch bark supplies, increase growth, replace limestone and micro-nutrients additions, and recycle a waste material.

SUMMARY

The aforementioned alternative substrate components can be used as a supplemental component to bark based nursery potting media. While no component can be used as a total bark replacement, each component has the potential to stretch bark supplies and result in equal or greater crop growth. In addition, many of the alternative substrates provide value-added to substrate mixtures by replacing limestone and micro-nutrients additions, as well as recycle a waste material with no current market value. When a tangible need for potting substrate alternatives is realized, whether for economic reasons or bark scarcity, the United States nursery industry has many research tested nursery ready alternate components to integrate in to their production systems.

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Literature Cited

Altland, J.E. and Krause, C. 2009. Use of switchgrass as a nursery container substrate. HortScience 44:1861-1865.

Altland, J.E. and Krause, C. 2010. Modification of switchgrass substrate pH using compost, peatmoss, and elemental sulfur. HortTechnology 20:950-956.

Altland, J.E. and Locke, J.C. 2011. Use of ground miscanthus straw in container nursery substrates. J. Environ. Hort. 29:114-118.

Baker, K.F. 1957. The U.C. System for Producing Healthy Container-grown Plants. Ed. California Agric. Expt. Sta. Extension Service Manual 23, Univ. California, College of Agriculture Publication, Berkeley, California U.S.A.

Boyer, C.R., Fain, G.B., Gilliam, C.H., Gallagher, T.V., Torbert, H.A. and Sibley, J.L. 2006. Clean chip residual: a new substrate component for container-grown plants. Proc. Southern Nursery Assn. Res. Conf. 51:22-25.

Boyer, C.R., Fain, G.B., Gilliam, C.H., Gallagher, T.V., Torbert, H.A. and Sibley, J.L. 2008. Clean chip residual: a substrate component for growing annuals. HortTechnology 18:423-432.

Boyer, C.R., Gilliam, C.H., Fain, G.B., Gallagher, T.V., Torbert, H.A. and Sibley, J.L. 2009. Production of woody nursery crops in clean chip residual substrate. J. Environ. Hort. 27:56-62.

Davidson, H., Mecklenburg, R. and Peterson, C. 2000. Nursery management: Administration and culture. 4th ed. Prentice Hall, Upper Saddle River, N.J.

Fain, G.B., Gilliam, C.H. and Sibley, J.L. 2006. Processed whole pine trees as a substrate for container-grown plants. Proc. Southern Nursery Assn. Res. Conf. 51:59-61.

Fain, G.B., Gilliam, C.H., Sibley, J.L. and Boyer, C.R. 2008. *Wholetree* substrates derived from three species of pine in production of annual vinca. HortTechnology 18:13-17.

Fonteno, W.C. and Bilderback, T.E. 1993. Impact of hydrogel on physical properties of coarse-structured horticultural substrates. J. Amer. Soc. Hort. Sci.118:217.

Furuta, T. 1974. Environmental Plant Production and Marketing. Cox Publishing Co., Arcadia.

Jackson, B.E., Wright, R.D., Browder, J.F., Harris, J.R. and Niemiera, A.X. 2008a. Effect of fertilizer rate on growth of azalea and holly in PB and pine tree substrates. HortScience 43:1561-1568.

Jackson, B.E., Wright, R.D. and Barnes, M.C. 2008b. Pine tree substrate, nitrogen rate, particle size, and peat amendment affects poinsettia growth and substrate physical properties. HortScience 43:2155-2161.

Jackson, B.E. and Wright, R.D. 2009. Changes in physical properties of a pine tree substrate in containers over time. Comb. Proc. Intl. Plant Prop. Soc. 58:93-98.

Jackson, B.E., Wright, R.D. and Barnes, M.C. 2010. Methods of constructing a pine tree substrate from various wood particle sizes, organic amendments and sand for desired physical properties and plant growth. HortScience 45:103-112.

Lu, W., Sibley, J.L., Gilliam, C.H., Bannon, J.S. and Zhang, Y. 2006. Estimation of U.S. bark generation and implications for horticultural industries. J. Environ. Hort. 24:29-34.

Lunt, O.R. and Kohl Jr., H.C. 1956. Influence of soil physical properties on the production and quality of bench grown carnations. J. Amer. Soc. Hort. Sci. 69:535-542.

Scott, E.G. and Bearce, B.C. 1972. A hardwood-bark-sawdust compost for greenhouse pot flower production. Forest Prod. J. 22:36-39.

Warren, S.L., Bilderback, T.E. and Owen Jr., J.S. 2009. Growing media for the nursery industry: Use of amendments in traditional bark-based media. Acta Hort. 819:143-155.

Wright, R.D., Browder, J.F. and Jackson, B.E. 2006. Ground pine chips as a substrate for container-grown wood nursery crops. J. Environ. Hort. 24:181-184.

Wright, R.D., Jackson, B.E., Browder, J.F. and Latimer, J.G. 2008. Growth of chrysanthemum in a pine tree substrate requires additional fertilizer. HortTechnology 18:111-115.

Yeager, T.H., Fare, D.C., Lea-Cox, J., Ruter, J., Bilderback, T.E., Gilliam, C.H., Niemiera, A.X., Warren, S.L., Whitwell, T.E., Wright, R.D. and Tilt, K.M. 2007. 2nd Ed. Best management practices: guide for producing container-grown plants. Southern Nurserymen's Assoc., Marietta, GA.

Tables

Table 1. Physical properties of pine bark (PB) and pine tree substrates (PTS) initially (at potting) and at 70 weeks after potting (WAP) in containers with plants when fertilized with 4.2 kg·m^{-3} of Osmocote Plus15N-3.9P-10K) and maintained under outdoor nursery conditions. Data are also reported for PTS in fallow containers at 70 WAP[z].

Substrates	Total porosity[y]	Air space[x]	Container capacity[w]	Bulk density[v]	Substrate shrinkage[u]
		(%)		(g·cm^{-3})	(%)
			Initial (at potting)		
PB	83.2 b[t]	26.4 c	56.8 c	0.18 b	-
PTS	91.2 a	35.9 a	55.3 c	0.14 d	-
			Final (70 WAP)		
PB w/ plant	83.3 b	19.7 d	63.6 a	0.21 a	16.3 b
PTS w/ plant	89.2 a	29.3 b	59.9 b	0.16 c	17.4 b
PTS fallow	87.5 ab	26.0 c	61.5 a	0.17 bc	22.3 a

[z] 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] Total porosity is equal to container capacity + air space.
[x] Air space is the volume of water drained from the sample ÷ volume of the sample.
[w] Container capacity is (wet weight – oven dry weight) ÷ volume of the sample.
[v] Bulk density after forced-air drying at 105°C for 48 h.
[u] Shrinkage = substrate height in container at 1 WAP - substrate height at 70 WAP.
[t] Means separated within columns using Duncan's multiple range test, $P \leq 0.05$ ($n = 3$).
[s] PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 4.76-mm screen.
[r] Suggested range for container substrates = Best Management Practices recommended sufficiency ranges for physical properties of substrates used in general container production (Yeager et al., 2007).

Tables

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PB w/ plant	83.3 b	19.7 d	63.6 a	0.21 a	16.3 b
PTS w/ plant	89.2 a	29.3 b	59.9 b	0.16 c	17.4 b
PTS fallow	87.5 ab	26.0 c	61.5 a	0.17 bc	22.3 a

[z] 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] Total porosity is equal to container capacity + air space.
[x] Air space is the volume of water drained from the sample ÷ volume of the sample.
[w] Container capacity is (wet weight – oven dry weight) ÷ volume of the sample.
[v] Bulk density after forced-air drying at 105°C for 48 h.
[u] Shrinkage = substrate height in container at 1 WAP - substrate height at 70 WAP.
[t] Means separated within columns using Duncan's multiple range test, $P \leq 0.05$ (n = 3).
[s] PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 4.76-mm screen.
[r] Suggested range for container substrates = Best Management Practices recommended sufficiency ranges for physical properties of substrates used in general container production (Yeager et al., 2007).

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Table 2. Physical properties of substrates, subsequent pH, and growth of hibiscus (*H. moscheutos*) in substrates comprised of 15% sphagnum peat moss, 5% municipal solid waste compost, and the remaining 80% comprised of varying ratios of pine (*Pinus taeda*) bark and miscanthus (*Miscanthus* ×*giganteum*) straw.

		Physical properties				Substrate pH			
Pine bark	Miscanthus straw	Air space	Container capacity (%)	Total porosity	Bulk density (D_b) ($g \cdot cm^{-3}$)	1 WAP[Z]	8 WAP	Shoot dry weight (g)	Root rating[W]
0	80	46	44	90	0.09	5.6	6.2	8.6	4.7
20	60	37	53	90	0.10	5.3	6.0	11.2	5.9
40	40	38	48	86	0.14	5.1	5.8	11.7	6.3
60	20	30	53	84	0.17	5.3	5.7	12.7	6.1
80	0	26	55	81	0.19	5.1	5.4	12.0	6.6
LSD[Y]		6	6	3	0.01	0.1	0.3	2.0	0.8
Trend[X]		L	L	L	L	L, Q	L	L,Q	L

[Z] WAP refers to weeks after potting.
[Y] LSD refers to Fisher's least significant difference value where $\alpha = 0.05$.
[X] Trend refers to the linear (L) or quadratic (Q) rate response to changing pine bark and miscanthus straw ratios.
[W] Roots were rated on a scale from 0 to 10 to characterize the percent of the substrate-container interface covered with living roots, where 0 = no roots visible and 10 = complete coverage of the substrate-container interface covered with roots.

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Table 3. Physical properties of substrates, subsequent pH, and growth of azalea (*A.* × 'Coral Bells') in substrates comprised of varying ratios of Douglas Fir (*Pseudotsuga menziesii*) bark and Douglas Fir timber slash.

		Physical properties				Substrate pH			
Douglas Fir bark	Douglas Fir timber slash	Air space	Container capacity	Total porosity	Bulk density (D_b)	1 WAP[Z]	6 WAP	Shoot dry weight	Root dry weight
			(%)		($g \cdot cm^{-3}$)			(g)	(g)
0	100	44	43	87	0.15	6.0	6.7	18.7	9.1
33	66	47	41	89	0.17	6.1	6.4	17.9	8.4
66	33	40	42	83	0.20	6.1	6.3	24.8	8.7
100	0	44	36	80	0.21	6.2	6.4	30.3	10.1
LSD[Y]		4	3	2	0.01	0.3	0.5	4.2	1.9
Trend[X]		NS	L, Q	L, Q	L, Q	NS	NS	L, Q	NS

[Z] WAP refers to weeks after potting.
[Y] LSD refers to Fisher's least significant difference value where $\alpha = 0.05$.
[X] Trend refers to the linear (L) or quadratic (Q) rate response to changing Douglas Fir bark and Douglas Fir timber slash ratios.

Table 3. Physical properties of substrates, subsequent pH, and growth of azalea (*A.* × 'Coral Bells') in substrates comprised of varying ratios of Douglas Fir (*Pseudotsuga menziesii*) bark and Douglas Fir timber slash.

		Physical properties				Substrate pH			
Douglas Fir bark	Douglas Fir timber slash	Air space (%)	Container capacity (%)	Total porosity (%)	Bulk density (D_b) ($g \cdot cm^{-3}$)	1 WAP[Z]	6 WAP	Shoot dry weight (g)	Root dry weight (g)
0	100	44	43	87	0.15	6.0	6.7	18.7	9.1
33	66	47	41	89	0.17	6.1	6.4	17.9	8.4
66	33	40	42	83	0.20	6.1	6.3	24.8	8.7
100	0	44	36	80	0.21	6.2	6.4	30.3	10.1
LSD[Y]		4	3	2	0.01	0.3	0.5	4.2	1.9
Trend[X]		NS	L, Q	L, Q	L, Q	NS	NS	L, Q	NS

[Z] WAP refers to weeks after potting.

[Y] LSD refers to Fisher's least significant difference value where $\alpha = 0.05$.

[X] Trend refers to the linear (L) or quadratic (Q) rate response to changing Douglas Fir bark and Douglas Fir timber slash ratios.

Table 4. Physical properties of substrates, subsequent pH, and growth of azalea (*A.* × 'Coral Bells') in substrates comprised of varying ratios of Douglas Fir (*Pseudotsuga menziesii*) bark and Christmas tree.

Douglas Fir bark	Christmas tree	Physical properties: Air space (%)	Container capacity (%)	Total porosity (%)	Bulk density (D_b) ($g{\cdot}cm^{-3}$)	Substrate pH: 1 WAP[Z]	6 WAP	Shoot dry weight (g)	Root dry weight (g)
0	100	44	36	80	0.21	6.5	7.0	14.9	7.2
33	66	45	42	87	0.18	6.1	6.9	18.7	8.0
66	33	49	41	90	0.16	6.1	6.9	24.2	8.3
100	0	55	35	90	0.14	6.2	6.4	30.3	10.1
LSD[Y]		3	2	2	0.01	0.4	0.4	3.7	1.4
Trend[X]		L, Q	Q	L, Q	L	NS	L	L	L

[Z] WAP refers to weeks after potting.
[Y] LSD refers to Fisher's least significant difference value where $\alpha = 0.05$.
[X] Trend refers to the linear (L) or quadratic (Q) rate response to changing Douglas fir bark and Christmas tree ratios.

Table 5. Effect of pine bark substrates amended with cotton stalk/swine compost (CCSW) on physical properties at 63 and 135 days after treatment initiation.[w]

CCSW	Total Porosity		Air Space		Container Capacity		Available Water		Unavailable Water		Bulk Density	
	Days after treatment initiation											
% by vol.	63	135	63	135	63	135	63	135	63	135	63	135
	% vol.										$g•cm^{-3}$	
0	84 *[x]	85*	33*	30*	52	55	22*	22*	29*	33*	0.26*	0.24*
15	84*	86*	29*	28*	55	58	24*	25*	30*	32*	0.25*	0.24*
30	85*	87*	29*	27*	56	60	24*	26*	32*	34*	0.23*	0.21*
45	86*	87*	24	25*	62*	62*	29	27*	33*	36*	0.23*	0.21*
8:1[y]	77	80	23	21	54.0	59	28	29	26	29	0.43	0.44
Trend[z]	L	L	L	L	L	L	L	L	L	L	L	L

[w] Warren et al., 2009.

[x] Significantly different from the control substrate [8:1 pine bark:sand (by vol.)] based on mean separation by Dunnett's test, $P = 0.05$.

[y] 8:1 pine bark:sand substrate by vol. The control substrate data not included in regression analysis.

[z] Trend refers to the linear (L) or quadratic (Q) rate response to changing.