Characterizing the Physical and Hydraulic Properties of Pine Bark Soilless Substrates

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Scientific Abstract

Soilless substrates, such as peat, pine bark, and coir, are widely used as growing media in containerized crops for their favorable characteristics, including low bulk density, balanced air exchange and water retention, disease resistance, and low pH and salinity. However, improper irrigation of these media can have negative outcomes such as root asphyxia, pathogen development, and reduced plant growth. Understanding pore size distributions, water dynamics, and gas diffusivity of these substrates is essential to promote plant growth. The effects of different particle sizes of soilless media on processes such as infiltration, hydraulic conductivity, and gas diffusivity are also not well understood. The characterization of these effects is important for the overall improvement of container crop production.

This thesis presents three studies that aimed to characterize the physical and hydraulic properties of pine bark substrates, both unamended and amended with peat or coir. The first study looked at three substrate types: unamended, unscreened pine bark, peat-amended pine bark, and coir amended pine bark. Three methods were employed to quantify pore distributions: non-equilibrium infiltration measurements, equilibrium water retention characterization, and scanning electron microscopy. We characterized pore distributions during wetting and drainage for the three substrates. Coir-amended bark had the largest water-conducting porosity, highest hydraulic conductivity, and most water retention. Unamended pine bark had the highest microporosity, and the addition of peat
and coir lowered macroporosity, with peat having the greater effect. The total porosity inferred from the infiltration method was significantly smaller than that inferred from drainage experiments due to assumptions related to pore shape.

The second study focused on defining hydraulic conductivity and water retention for pine bark substrates of five different particle sizes, <1 mm, 1-2 mm, 2-4 mm, 4-6 mm, and an unscreened fraction. We utilized the same methods from the first study. The resulting data showed that the smallest particle sizes (i.e., <1 mm and 1-2 mm) had the highest hydraulic conductivity and greatest water retention. The three larger sizes had lower hydraulic conductivity and poor water retention, including the unscreened fraction, which more closely followed the results of the 2-4 mm size.

The final study examined gas diffusivity of the five pine bark particle sizes at different moisture levels: 60% moisture content (initial conditions), saturated at the bottom of the sample, near-saturated at the sample bottom, and drained fromsaturation to container capacity. We used a one-chamber gas diffusion setup to find gas diffusion coefficients ($D_s$). The results displayed an inverse relationship between $D_s$ values and substrate water content. In addition, the larger particle sizes were less sensitive to changes in water content due to their well-draining large pores.

Proper balance of aeration and water retention is necessary for the success of soilless growing media. Overall, the smaller particle size fractions had the best water retention and hydraulic conductivity rates while the larger fractions had the largest $D_s$ coefficients. This work contributes valuable knowledge on the physical and hydraulic properties of different size fractions of pine bark substrates, which can assist nursery growers in optimizing water usage for sustainable container crop production.
Characterizing the Physical and Hydraulic Properties of Pine Bark Soilless Substrates

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Public Abstract

Since the 1950’s soilless substrates have been an important resource for growing a variety of fruits, vegetables, flowers, and ornamental plants. Soilless growing media have become more popular choices for containerized plant production compared to natural soils due to improved air exchange, increased disease resistance, and more plants per acre. They are also favored because they help conserve resources, reduce agricultural waste, and minimize transportation requirements as compared to traditional cropping methods. The most popular types of soilless media include peat, coir, compost, and pine bark. In the U.S., pine bark is the main substrate used, as it is renewable and widely available.

Growers still face many issues when using containerized crop production. For example, pine bark is susceptible to water runoff which can cause environmental problems and increase costs from this loss of water and fertilizer. Further characterizing of water and gas dynamics in of pine bark growing media is important for conserving water and fertilizer resources while optimizing plant growth in this container cropping industry. Pore characteristics, aeration, and water movement are key factors of substrates to be described to solve these challenges.

This project aimed to apply soil physics strategies to soilless media, focusing on describing pore sizes, water movement, water holding capacity, and air movement in pine bark substrates. We utilized three methods throughout this study. For the first method, we took infiltration measurements to examine how water moved into the media, while the
second utilized controlled drainage experiments to observe how water moved out of the media. The final method was characterizing gas movement through the substrates at different water contents and particle sizes.

The results found showed that the smaller particle sizes and pine bark mixed with peat and coir had increased ability to retain water and allow water movement as compared to the larger particle sizes and unamended pine bark. In contrast, the larger particles had less water retention but improved gas movement. These results could be applied by stacking different particle sizes or mixes over one another could optimize water retention in the top of the container and drainage and gas movement in the bottom of the container. Overall, the application of this work is to create best management practices for growers to be able to balance water retention and gas movement in order to optimize plant growth.
Acknowledgments

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I would like to send the biggest thank you to my friends and family for always championing my interests and being a constant pillar of support. Finally, my animals Juniper and Hamish who were my biggest supporters through this journey.
Dedication

I would like to dedicate this work to my grandparents Oliver and Linda Wolcott, who supported and encouraged my education always.
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1. Introduction

When describing the vast variety of scales on which hydrological processes operate, Horton (1931 p.192) depicted a plethora of natural and exposed surfaces: trees, a single leaf on a plant, river system watershed, glacier, swamp, ocean, lake, sand dunes, or earth as a whole. Containerized crop production is a worthy addition to this list of systems. There is a necessity to understand the diversity of the hydrologic cycling within a nursery system. Currently, agriculture accounts for an average 70% of all freshwater use globally (“Water in Agriculture,” 2022). Containerized crop production is a part of this usage as it relies greatly on surface and groundwater sources for irrigation needs (Majsztrik et al., 2017).

The world population world is currently ~7.8 billion and is projected to increase to 9 to 10 billion by 2050. With this many people and their increasing affluence, total food consumption will increase by 50-70% (Stanghellini, 2014). Any means of optimizing food production by unit area will be important to accommodate the increased population burden (Jaggard et al., 2010). The majority of the world’s crops are grown in naturally formed soil. Globally, 38% percent of land contains arable soil for producing food for the entire population of the world (FAO, 2020). Poor soils of the world, which are characterized by excessive compaction, limited drainage, unstable amounts of erosion, presence of disease and pests, and other factors, restrict plant growth (Hussain et al., 2014). How do we produce food in low quality areas that aren’t usually suitable for growing? Containerized crop production is one possible ally in this impending crisis. Urban areas, industrial areas, areas with low fertility, and land with unfavorable
geographic or topographic conditions are all examples of places where soilless containerized crop production has an opportunity to be implemented.

According to the European Committee for Standardization (1999), the definition for soilless growing media is materials other than soils utilized in situ. These are bulk materials used in the creation of soilless media and have consistent properties for each product produced (Carlile et al., 2015). The materials of soilless culture provide arable conditions, low bulk density, mechanical support, and stable properties for short term crops, i.e., those cultivated for months to a few years (Wang et al., 2013). Constituents that can potentially make up soilless media are available around the globe and provide protection against pests and disease (Carlile et al., 2015). Soil borne pests and diseases are not easily transferable to container production (Hussain et al., 2014). Individual pots create separation of contamination and a decrease in pests and disease, which allows for an increase in plant growth in relation to conventional cultivation methods (Blok et al., 2021).

Soilless culture methods have another unique advantage over naturally formed soils: the ability to adjust individual containers to provide optimal conditions for plant growth and elevate yields (Hussain et al., 2014). Each container can be mixed, packed, fertilized, and watered according to the necessary conditions for the specific plant and climatic conditions. Plants can be grown throughout the year and at higher densities than outdoor crops and the root zone nutrient application is more easily modifiable in comparison to field production (Majsztrik, 2011; Majsztrik et al., 2017). Soilless media allows for a level of precision in water and nutrient application that allows for up to 15% increase in growth by applying small amounts of water frequently per plant (Blok et al.,
Soilless media has great potential to be used in developing countries where water supply issues make growing in a large-scale landscape setting unfeasible (Hussain et al., 2014).

However, in the U.S. and other countries in the global north, containerized systems use a large amount of water as they must be irrigated more frequently than traditional cropping methods due to their high porosity and restricted root volumes. This excess irrigation produces runoff that may impact surface and groundwater sources (Majsztrik, 2011). Systems exist which capture and reuse this leachate for rockwool substrates, but at significant cost (Owen and Altland, 2008; Majsztrik, 2011). When used in conjunction with water collection and recirculation methods, water use in production systems utilizing rockwool substrate can be reduced by 50% and nutrient use can be reduced by 60% relative to field crops (Blok et al., 2021). With these advantages, producers and researchers of growing media expect the market for soilless substrate market to expand to fill the needs of the growing world population (Blok et al., 2021).

The past 50 years has seen containerized crop production become one of the fastest growing sectors of agriculture (Hussain et al., 2014; Majsztrik et al., 2017). There are a wide variety of soilless substrates used in this industry including peat, coir, pine bark, rockwool, perlite, and others. These substrates can be used singularly or as blends. Peat-based substrates are the favored organic substrate in many countries around the world, especially Europe and Canada. These substrates are partially degraded organic material collected from peat bogs (Carlile et al., 2015). Coir is a material collected from the fibrous middle layer of coconut fruit (Carlile et al., 2015). It is known for its hydrophilic (i.e., fully wettable) nature and greater proportion of easily available water (¬
10 to -100cm), but preparation for use as a substrate is water and labor intensive (Hirschler et al., 2022). Pine bark soilless substrates have been utilized for decades and have become an important component of the economy of containerized crop production in the United States nursery industry (Bilderback et al., 2013). However, pine bark processing can vary between suppliers, which affects the associated physical properties of the product (Bilderback et al., 2005). In addition to screening and subsequent particle size distribution, the two of the most important and controlled production factors for pine bark properties are the aging process and source of the pine bark (Bilderback et al., 2005; Altland et al., 2018). Breakdown of pine bark by particle size and the subsequent effects particle size has on water and gas movement in a container has not yet been quantified.

Past studies quantifying the physical properties of soilless substrates often focus on static properties like those collected from a porometer. The porometer was developed at a North Carolina State University to repeatedly and easily characterize static properties of pine bark- and peat-based soilless substrates. It uses a 7.6 cm tall cylinder with a drainable base to calculate minimum air space and maximum water holding capacity of substrates (Fields et al., 2020). Porometers have been successfully used for media characterization, however these instruments do not adequately quantify variable properties such as hydraulic conductivity and gas diffusion. Unsaturated hydraulic conductivity and gas diffusivity need to be examined through time in order to inform proper substrate engineering for a balance of water retention and air diffusivity (Fields et al., 2020).

This project aims to measure the hydraulic and gas diffusion characteristics of three soilless substrates, pine bark, coir-amended pine bark and peat-amended pine bark,
through various wetting procedures to understand how water and air moves into, through, and out of these substrates. Previous research has focused on water retention to limit runoff, pollution, and loss of resources from the containers. In this work, in Chapter 2 we focus on hydraulic conductivity and water retention of substrates of different mixes, pine bark, peat + pine bark, and coir + pine bark. In Chapter 3, we examined the same characteristics of hydraulic conductivity and water retention as well as water repellency of unamended pine bark of five different particle sizes. Finally in Chapter 4, gas diffusion measurements were taken to compare the five particle sizes of unamended pine bark under different water contents. All of this data will be used to advise nursery and greenhouse growers to create better management practices for containerized crop production.
2. Quantifying functional pore sizes in pine bark growing media


Abstract

Water limitations and concerns about nutrient runoff are important reasons nursery producers must select substrates with proper water-holding and infiltration properties. Pore size distribution is a crucial property influencing water dynamics within soilless growing media. Pore sizes can be determined using equilibrium-based measurements, such as drainage water retention experiments. Another approach involves non-equilibrium infiltration measurements, typically with water supplied under tension, which can better identify pores that become dynamically activated during wetting events. In this study, we compared two procedures to quantify pore sizes in a pine-bark substrate that was unamended versus amended with peat or coir. The first procedure used drainage measurements with a hanging water column to create moisture retention curves. The second procedure involved interpreting measurements collected from a tension infiltrometer at three source tensions and saturation. The two approaches provided different yet complementary estimates for pore size distributions. The tension infiltrometer-based measurements implied that only a small proportion of the total pore space was involved during infiltration, with water-conducting porosities of $<10^{-4} \text{ cm}^3 \text{ cm}^{-3}$. Both methods indicated that coir may be a particularly useful amendment since it retains some macro-porosity (which is useful for allowing gas exchange in wet media).
while increasing the water retention of the pine bark substrate. These results can guide future efforts to characterize and optimize growing media such as pine bark substrates, with the end goal of maximizing nursery production while minimizing pollution and water losses.

2.1 Introduction

Organic soilless growing media is favored in containerized production due to its low bulk density, aeration quality, resistance to diseases and pests, and relatively low pH and salinity. Peat and bark are primarily utilized in greenhouse or nursery settings for the cultivation of a variety of plants, including woody ornamental crops, vegetables, floriculture, and fruit trees (Carlile et al., 2015). Cultivating plants using soilless substrates, which are not naturally formed soil, is associated with increased resource conservation, decreased industrial and regional agricultural wastes, and reduced transportation burdens as compared to traditional field production methods. (Raviv, Fonteno and Bilderback, 1993). However, soilless media can also pose challenges when improperly irrigated. Too much water can lead to root asphyxia, development of pathogens, or wasted agrichemicals due to leaching, whereas too little water causes reduced growth and time to market due to plant physiological stress (Kerloch and Michel, 2015; Michel and Kerloch, 2017). Better understanding of water dynamics in growing media is therefore necessary to avoid these issues.

Pine bark-based substrates are the favored organic growing media in many parts of the United States (USA), France, Spain, New Zealand, and Australia (Carlile et al., 2015). Advantages of pine bark include a lower cost compared to peat, a larger range of
particle sizes that provide the needed air-filled porosity and capillary water, and suppression of pathogens (Raviv et al., 1986; Handreck et al., 2002). However, pine bark is also susceptible to formation of water repellency and can have decreased water-holding capacity after repeated wetting and drying cycles (Altland et al., 2018). Therefore, surfactants or additional soilless media (e.g., peat or coir) are often added to pine bark substrates. The addition of peat to bark-based substrates is mainly used to increase water-holding capacity (Handreck et al., 2002). However, peat becomes water repellent when drying (Michel et al., 2008) and is not found in the continental U.S. In addition, many substrate companies are looking to phase out use of peat in efforts to minimize their carbon footprints and transportation costs (Durand et al., 2021). Another common amendment is coir substrate, a media that comes from coconut fibers in tropical regions. Coir is known to be hydrophilic, unlike dry peat and pine bark, but has comparable water-holding properties to wet peat. A negative of this substrate type is that coir contains elevated concentrations of salt and requires intensive washing before horticultural use; a process which utilizes large amounts of water. Additionally, transport from tropical regions where coconuts can grow creates a added financial burden (Hirschler et al., 2022).

Soilless substrates often exhibit complex hydraulic behaviors, including loss of available pore space and formation of preferential pathways through repeated wet and dry cycles (Naasz et al., 2005, 2009). When applying water and fertilizer together (i.e., fertigation), preferential flow through these pathways can result in excess leaching of mineral nutrients and decreased profitability of the growing operation (Hoskins et al., 2014). Hysteresis is another important consideration, as water retention properties often
vary greatly depending on whether the medium is wetting or drying due to effects such as non-uniform pores, trapped air, and water repellency (Fields et al., 2020). Macropores, which we consider here to be pores ≥0.3 mm in effective radius (0.6 mm in diameter), are another source of complexity. Macropores easily drain and can help improve gas exchange of a substrate, but they can also lead to preferential movement and drainage of water and mineral nutrients (Hoskins et al., 2014). Macroporosity size and connectivity are also important factors determining the hydraulic conductivity and infiltration capacity of a porous medium (Buczko et al., 2006).

All the above-mentioned factors are related to pore characteristics, making it critical to have suitable methods to quantify and understand how pore structure and size distributions influence water retention, water availability to plants, and water movement through soilless substrates. This project seeks to apply soil physics methods to soilless media in order to gain a better understanding of the hydraulic and physical properties of the substrates. The goal of this study was to characterize the baseline properties of pore size, hydraulic conductivity, and moisture retention curve for a pine bark substrate that was unamended versus amended with peat or coir. We used two different methods of quantifying macropore distributions under equilibrium (i.e., during controlled drainage) versus non-equilibrium (i.e., during infiltration) conditions in order to determine which pore sizes and volumes are activated under different moisture conditions.

2.2 Methods

Sourcing Substrates
Aged, stabilized pine bark (≤12.7 mm) substrate made up the base of each of the three substrate types in this experiment (the bark was processed by Pacific Organics, Henderson, NC, USA). The first substrate studied consisted of the substrate as prepared (i.e., unamended pine bark). The second substrate was mixed with surfactant-treated Sphagnum peat (Sun Gro Horticulture, Agawam, MA, USA) in a 70 pine: 30 peat (by. vol.) mixture. The third substrate was a 70 pine: 30 coir (Sun Gro; by. vol.) mixture (Figure 2.1). The three substrates were prepared at the USDA ARS facility in Wooster, OH, USA, and were brought to a consistent moisture content of 55-60%. Bulk density, air space, container capacity, total porosity, gravimetric water content, volumetric water content, and moisture content for each substrate were measured using porometers (Fonteno and Bilderback, 1993). Substrates were kept sealed in 18.9 L (5 gal) buckets at 7°C until the experiments began.

Figure 2.1. Examples of the three substrates analyzed in this study, including an unamended pine bark, pine bark amended with peat (70:30% pine bark:peat by. vol.), and pine bark amended with coir (70:30% pine bark:coir by. vol.).
Scanning Electron Microscopy

Scanning electron microscopy (SEM) was utilized to characterize particle size and shape on a microscopic scale. We used a HITACHI Tabletop Microscope (TM3000) to collect magnified images of the substrate. Each substrate was placed on double sided conducting sticky tape to hold the substrate to the plate. During SEM scans, we captured images that conveyed differences in particle size and shape between the three substrates.

Non-equilibrium infiltration tests

Infiltration tests were conducted with a Mini-disk Tension Infiltrometer (METER Group, Pullman, WA, USA). The substrates were packed to a uniform bulk density of approximately 0.13 g cm\(^{-3}\) inside of clear polycarbonate plastic tubes with an inner diameter of 4.0 cm and a height of 15 cm. A layer of fine silica sand (250 \(\mu\)M) was placed on top of the substrate surface to ensure a good hydraulic connection. The infiltrometer was set to a specific tension and then placed firmly on the sand surface. We used three different tensions, –5 cm, –3 cm, and –1 cm, and ran each test for 30 minutes or until the wetting front reached the bottom of the cores (i.e., when water began draining from the core). Water levels in the infiltrometer were recorded every 30 seconds. We ran each substrate type at approximately 60% moisture content, where moisture content was calculated as the mass of water over mass of water plus substrates. At the conclusion of each test, we then saturated the columns and ran the tests with the source tension = 0 cm, to determine the saturated hydraulic conductivity, \(K_s\).

Equilibrium water retention characterization

Tempe pressure cells (SoilMoisture Equipment Corp., Santa Barbara, CA, USA) were utilized to determine water retention properties during drainage. We packed cells to
a bulk density of around 0.13 g cm$^{-3}$ by spooning the substrate into them and then tapping three times on the top of the wooden hanging column structure after each spoonful. Water was drawn from the cells at varying tensions with the goal of draining progressively smaller pores. The bottom of each Tempe cell was connected to a drainage line (i.e., hanging water column), and the outlet was fixed at heights of –5 cm, –10 cm, –15 cm, –25 cm, –50 cm, and –100 cm (relative to the midpoint of the core). The water was collected and weighed after each height was allowed to drain for two hours. As the water is held under different tensions, the ability for plants to access this water changes. As such, we have categorized four pools of water availability under these six tensions. Container capacity (CC) is 0 to -10 cm, easily available water (EAW) is -10 to -50 cm, water buffering capacity (WBC) is -50 to -100 cm, and unavailable water (UAW) is -100+ cm (Caron and Michel, 2021).

**Analysis**

The hydraulic conductivity associated with each source tension, $K(h)$, was estimated from the mini-disk infiltrometers by assuming that infiltration had reached steady-state conditions by the end of the test:

$$I(h) = K(h) \times t + c$$

where $I(h)$ is the cumulative infiltration for each test, $t$ is the elapsed time, and $c$ is a constant. $K(h)$ and $c$ were determined by applying linear regression to the final 4-10 observations of $I(h)$ and $t$.

The water-conducting porosities, $\varepsilon_{wc}(h_1,h_2)$, were next calculated by applying estimated $K(h)$ values to the model developed by Bodhinayake (2004) and assuming a
unit gradient:

$$\varepsilon_{wc}(h_1, h_2) = \frac{2 \mu \rho g}{\gamma^2} \int_{h_1}^{h_2} \frac{dK(h)}{dh} h^2 dh$$

where $\mu$ is the fluid dynamic viscosity, $\rho$ is the fluid density, and $\gamma$ is the fluid surface tension.

Equation (2) can be solved numerically or using an analytical solution. Here we used the Brooks and Corey (1964) model in which $K(h)$ is expressed as:

$$K(h) = K_s \quad \text{if } h \geq h_b$$

$$K(h) = K_s \left( \frac{h_b}{h} \right)^{\eta} \quad \text{if } h < h_b$$

where $h_b$ is the bubbling pressure ($h_b < 0$) and $\eta$ is a parameter related to the pore size distribution ($\eta > 2$).

Substituting Equation (3) into (2) and solving leads to:

$$\varepsilon_{wc}(h_1, h_2) = \left( \frac{2 \mu K_s (\rho g)^{\eta-1}}{(2\gamma)^{\eta}} \right) \left( \frac{2\gamma^{\eta-2}}{\rho g h_2} - \frac{2\gamma^{\eta-2}}{\rho g h_1} \right) \left( \frac{\eta}{\eta-2} \right)$$

(4)

To apply Equation (4) we first used least-squares regression to fit Equation (3) to the mean $K(h)$ values measured at each source tension. We then applied the estimated $h_b$ and $\eta$ values to Equation (4).

The estimated $h_b$ and $\eta$ parameters were also used to model the main wetting curve of each substrate, using the Brooks and Corey (1964) water-retention curve expression and assuming that residual water content was negligible:

$$\theta(h) = \theta_s \quad \text{if } h \geq h_b$$

$$\theta(h) = \theta_s \left( \frac{h_b}{h} \right)^{\frac{\eta-2}{3}} \quad \text{if } h < h_b$$

(5)

The hanging water column data were used to estimate the porosity distributions associated with water drainage, $\varepsilon_d(h_1, h_2)$, by:
\[ \varepsilon_d(h_1, h_2) = \theta(h_1) - \theta(h_2) \]  \hspace{1cm} (6)

where \( h_1 \) and \( h_2 \) are different pressure heads and \( \theta(h_1) \) and \( \theta(h_2) \) are the corresponding volumetric water contents.

We converted pressure heads to corresponding equivalent pore radii, \( r_i \), using the Young-Laplace relationship for a capillary tube:

\[ r_i = \frac{2y}{\rho g h_i} \]  \hspace{1cm} (7)

We also determined the maximum pore radius in each substrate (\( r_{max} \)) using the calculated \( h_b \) value:

\[ r_{max} = \frac{2y}{\rho g h_b} \]  \hspace{1cm} (8)

Finally, we estimated the macroporosity of each substrate as:

\[ \varepsilon_{mp} = \phi - \theta(h = -5 \text{ cm}) \]  \hspace{1cm} (9)

where \( \phi \) is the substrate porosity and \( \theta(h = -5 \text{ cm}) \) is the water content after drainage at pressure head = –5 cm. Note that, based on Eq. (7), macropores were considered to be any pore with \( r \geq 3 \times 10^{-4} \text{ m} \) (0.3 mm).

2.3 Results and Discussion

Porometer Data

The three mixes were packed to very similar bulk densities. Pine bark had the greatest percent soils and air space as compared to the two amended mixes. The coir and peat mixes had much greater container capacity, which aligns with previous studies and their typically greater water storage capabilities as compared to pine bark. The total porosities of all three were similar, but coir had the greatest.
Table 2.1 Static physical properties of the three substrate mixes from porometer data collected by USDA ARS colleagues.

<table>
<thead>
<tr>
<th></th>
<th>Percent solid (cm³/cm³)</th>
<th>Air space at container capacity (cm³/cm³)</th>
<th>Container capacity (cm³/cm³)</th>
<th>Total porosity (cm³/cm³)</th>
<th>Bulk density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat + pine</td>
<td>0.19</td>
<td>0.24</td>
<td>0.55</td>
<td>0.79</td>
<td>0.14</td>
</tr>
<tr>
<td>Coir + pine</td>
<td>0.21</td>
<td>0.20</td>
<td>0.60</td>
<td>0.80</td>
<td>0.15</td>
</tr>
<tr>
<td>Pine bark</td>
<td>0.25</td>
<td>0.30</td>
<td>0.46</td>
<td>0.76</td>
<td>0.16</td>
</tr>
</tbody>
</table>

**Scanning Electron Microscopy**

The images collected with the SEM showed that the three substrate mixes contained an interesting variety of particle shapes (Figure 2.2). The pine bark particles were elongated and rectangular with rough, rounded edges (Figure 2.2a). Upon higher magnification, the pine bark fragment did not have much visible micro-scale pore space, which is important for water-holding capacity (Figure 2.2d). The peat+pine bark mixture included thin cylindrical shapes along with the elongated rectangular shapes (Figure 2.2b). The higher magnification revealed that the peat particles had a sponge-like texture (Figure 2.2e). The coir+pine mixture contained cylindrical fibrous shapes as well as the rectangular pine particles (Figure 2.2c). The magnification of the coir mix showed that many of the elongated particles were aggregated, creating micro-scale pore space that likely enhances the water retention properties of the substrate (Figure 2.2f). Note that the light-colored areas on the substrates represent metals (likely iron oxides) adsorbed to the organic matter.
Hydraulic conductivity

We calculated $K(h)$ for each substrate and tension using Eq. (3). The coir mixture had a greater $K_s$ value than the other two substrates, a similar $K$ value to the other mixes at $h = -1$ cm, and much a larger $K$ value at $h = -3$ cm (Figure 2,3). The peat mixture had a larger $K_s$ value than the pine bark but had similar $K$ values as the pine bark for $h \leq -1$ cm. The three substrates had similar estimated $K$ values for the $h = -5$ cm tests; however, those values had considerable uncertainty compared to the others due to the relatively short duration of the tests (30 minutes) and the possibility that the infiltration flux was not at steady-state at that time. Nonetheless, the results from the other tensions indicate
that the coir amendment had a more substantial effect on unsaturated hydraulic conductivity and water movement compared to peat. The generally larger K values observed for the coir mixture may reflect the greater wettability of that material compared to the other two substrates, or possibly greater connectivity between relatively fine pores in the material matrix due to the addition of coir.

Figure 2.3. Unsaturated hydraulic conductivity, $K(h)$, of the three substrates. The points indicate values measured from infiltration tests at different source pressures; dotted lines indicate model fits using the Brooks and Corey (1964) model, Eq. (3). Each point on the line represents the mean of at least three samples.

**Water retention characteristics**

The three substrate mixes had similar porosity values ($\phi = 0.66 – 0.70 \text{ cm}^3 \text{ cm}^{-3}$),
but their water-retention behaviors were different during the drainage experiment (Figure 2.2). The peat and coir mixtures retained similar water contents throughout the range of applied tensions, e.g., $\theta = 0.69 - 0.73$ cm$^3$ cm$^{-3}$ at $h = -100$ cm. Peat had the best water retention through all the water availability pools. The pine bark had substantially less water retention than the other two mixtures, reaching $\theta = 0.60$ cm$^3$ cm$^{-3}$ at $h = -100$ cm. These results reflect previous observations (Fields et al., 2018) and underscore how water retention properties of pine bark can be improved via the addition of peat or coir.

The Brooks and Corey parameters estimated from the tension infiltration tests were also applied to approximate the main wetting curves of the substrates. All three modeled wetting curves had large increases in water-filled porosity for $h > -5$ cm (Figure 2.4). Calculated bubbling pressures ($h_b$) were $> -1$ cm for all substrates, as would be expected for these materials given the large pores that existed between many particles (Figure 1). The unamended pine bark had the lowest water contents for any given pressure head during wetting, and the peat-pine bark mixture had the highest water contents, thus providing similar relative behaviors as the drainage curves.
Figure 2.4. Water retention curves for the three substrates based on drainage measurements (solid lines) versus wetting data (dashed lines) estimated from Eq. (5) using parameters estimated from infiltration tests. Each point on the drainage curves represents the mean of at least three samples. The arrows represent the three pools of water availability: air volume at container capacity (AV), easily available water (EAW), and water buffering capacity (WBC).

**Effective pore-size distributions**

The infiltrometer data were also analyzed using Equation 6 to quantify the water-conducting porosity, $\varepsilon_{wc}$. This parameter depicts the total volume of pore space that becomes activated over a given tension range. The coir mixture had the largest calculated pore size, $r_{max} = 2.7 \times 10^{-3}$ m (Figure 2.5). The other two substrates had nominally
smaller $r_{max}$ values, around $2.3 \times 10^{-3}$ m (peat mixture) and $1.9 \times 10^{-3}$ m (unamended pine bark). The coir mixture had a porosity of $5.0 \times 10^{-5}$ cm$^3$ cm$^{-3}$ associated with the largest pores (i.e., $r > 1.5 \times 10^{-3}$ m), which represents an increase of 15% relative to the peat mixture (porosity of $4.4 \times 10^{-5}$ cm$^3$ cm$^{-3}$) and 52% relative to the unamended pine bark (porosity of $3.3 \times 10^{-5}$ cm$^3$ cm$^{-3}$). Therefore, the addition of coir caused a substantial increase in the amount of porosity that became activated during these infiltration tests (explaining the differences in $K(h)$ measured for coir versus the other two substrates), whereas the peat had little-to-no effect on water-conducting pores compared to the unamended bark.

Figure 2.5. Water-conducting porosity ($\varepsilon_{wc}$) as a function of pore size, $r$. Each tension activates a known pores size. At each of these pore sizes, an amount of water conducting porosity is measured. Coir had the largest $\varepsilon_{wc}$ at the largest pore size. Therefore, coir allows for the most water to move through the macropores in comparison to the other two substrate types. Note that pores with $r \geq 3 \times 10^{-4}$ m were macropores, $\varepsilon_{mp}$, per Eq. (9).
The porosity estimated from the water retention experiment, \( \varepsilon_d \), indicated large differences in the amount of macro-porosity \( \varepsilon_{mp} \) (i.e., \( r \geq 3 \times 10^{-4} \) m; Figure 2.6). The pine bark had the greatest apparent macro-porosity volume (\( \varepsilon_{mp} = 0.13 \) cm\(^3\)cm\(^{-3}\)), due to the large decrease in \( \theta \) between saturation and \( h = -5 \) cm. By comparison, the addition of peat caused \( \varepsilon_{mp} \) to decrease to 0.01 cm\(^3\) cm\(^{-3}\), and the addition of coir resulted in an intermediate value of \( \varepsilon_{mp} = 0.07 \) cm\(^3\) cm\(^{-3}\). Porosity distributions also differed for pore sizes between \( 1.5 \times 10^{-4} \) and \( 3 \times 10^{-4} \) m: pine bark had the greatest porosity with \( \varepsilon_{mp} = 0.092 \) cm\(^3\) cm\(^{-3}\), peat next with \( \varepsilon_{mp} = 0.076 \) cm\(^3\) cm\(^{-3}\), and coir had the least with \( \varepsilon_{mp} = 0.056 \) cm\(^3\) cm\(^{-3}\). Calculated \( \varepsilon_d \) values were similar for the three mixtures for smaller pore sizes \( (1.5 \times 10^{-5} \leq r \leq 1.5 \times 10^{-4}) \). These results suggest that coir may be a particularly useful amendment since it retains some macro-porosity (which is useful for allowing gas exchange in wet media) while increasing the water retention of the pine bark substrate.

Figure 2.6. Porosity distribution values associated with water retention (\( \varepsilon_d \)) for each substrate as determined by the equilibrium drainage method (i.e., hanging water
column). Note that pores with \( r \geq 3 \times 10^{-4} \) m were macropores, \( \varepsilon_{mp} \), per Eq. (9).

For the macropores, pine bark had the most water moving and draining. Peat had the least amount of microporosity as it filled in the spaces between the pine bark. Coir was able to retain some microporosity and allow for flow through the large pores.

The equilibrium and non-equilibrium methods had some similarities and differences for their results of pine bark mixes. The estimates for pore-size distributions showed that the unamended pine bark had the most macro-porosity \( (r \geq 3 \times 10^{-4} \) m) and the peat-pine bark mixture had the least. However, the porosities calculated from the equilibrium water-retention experiment were 3 to 4 orders of magnitude higher than those calculated using the non-equilibrium infiltration tests (see Figures 2.5 and 2.6). This result was not entirely unexpected, as previous work has shown similar discrepancies between these methods (Bodhinayake and Si, 2004; Buczko et al., 2006; Carey et al., 2007). For example, Buczko et al. (2006) found that macro-porosities derived from water retention characteristics (i.e., a hanging water column) were greater than those derived from tension infiltrometry by a factor of 1000.

The contrasting porosity values likely reflect the complexity of pores within these substrates. The conceptual models used in this analysis assumed that substrate pores were cylindrical tubes, which oversimplified the complex, often angular pores that existed between particles (Figure 2.2). We also assumed a negligible contact angle in Eq. 7, even though the actual contact angle associated with the tension infiltration tests was likely non-negligible. Nonetheless, the substantial differences in magnitudes between the two
approaches imply that only a small portion of the total porosity may be actively conducting water during these flow experiments.

Another way to interpret these results is that, although both measurements are primarily influenced by pore necks (i.e., the narrowest portions of the pores), the data interpretation are very different. During the drainage process, the larger pore bodies would likely have drained once the capillary pressure of a given pore neck was overcome (Selker et al., 1999). This means that relatively large pore volumes were associated with a given pore size (light blue areas in Figure 2.7). The pore necks were also important to the infiltration process, since they act as the most restrictive portion of the water-conducting pathway (Carey et al., 2007). However, Eqs. (2) and (5) were derived assuming cylindrical pores. Therefore, this approach prescribed the minimum possible volume to each water-conducting pore (cylindrical tube depicted in Figure 2.7). The model also neglected any tortuosity in the pores, which would have increased the porosity, albeit by a small factor of around 1.5 to 3x (Basset et al., 2019). Accurately tracking changes in volumetric water content within the substrate during the infiltration process could be a better, or at least complementary, way to quantify the portion of the pore space that becomes activated during wetting.
Figure 2.7. Conceptual diagram showing how the equilibrium and non-equilibrium methods operate when characterizing the same irregularly shaped pore space. During the equilibrium drainage experiment, water will drain from the entire pore once the capillary potentials of the pore necks are exceeded, as indicated by the drainage-associated porosity ($\varepsilon_d$). The infiltration tests, by contrast, infer water-conducting porosity ($\varepsilon_{wc}$) based on the hydraulic resistance of the pore necks with the assumption that the pore is cylindrical. As a result, $\varepsilon_d$ can be many times greater in magnitude than $\varepsilon_{wc}$.

2.4 Conclusions and Implications

In this study, we compared two approaches for characterizing pore size distributions in pine bark that was unamended versus amended with peat or coir. One method relied on non-equilibrium infiltration measurements on relatively dry material (initial moisture contents of 60%), whereas the other method relied on drainage of
initially saturated media until reaching equilibrium water contents (i.e., when drainage ceased) at progressively lower water potentials. The use of a tension infiltrometer at different source tensions activated increasingly larger pores during water flow and allowed us to quantify the portion of the pore space that conducted water. Results of both methods indicated that pine bark had the most macroporosity, defined here as pores with effective radii larger than $3 \times 10^{-4}$ m (0.3 mm). The addition of peat reduced macroporosity by a substantial amount. The total amount of porosity that was inferred using the infiltration method was 3 to 4 orders of magnitude smaller than that inferred from the drainage experiments, even though the substrates had been packed with equal bulk densities.

The difference in magnitudes of $10^{-2}$ and $10^{-5}$ was primarily caused by limitations of the assumptions that were inherent to these methods. The biggest inconsistencies were related to the assumption that the pores were cylindrical tubes, which was inconsistent with the actual pore shapes observed using SEM. This assumption resulted in an underestimation of the water-conducting porosity distributions based on the tension infiltrometer tests. Future work could therefore aim to reconcile the calculated water-conductivity porosity values with the actual increases in water content that occur during these controlled flow conditions.

Despite such discrepancies, the two methods explored here offer insight into important hydraulic properties of the growing media. The porosity distributions characterized by infiltrometer data can be considered to represent the hydraulically active porosity, which is the minimum amount of pore space needed for water to move through the material. The hanging water column experiment also quantifies portions of the pore
space that may be filled with water but does not actively influence water flow. This ‘non-active’ pore space may act as a water supply for plants growing in the media, depending on its ability to become filled and retain water during irrigation or other water application. Therefore, future work may specifically consider how these different portions of the pore space influence plant water uptake and growth.
3. Hydraulic conductivity, wettability, and water retention of different size fractions of a pine bark substrate

Abstract

Pine bark that has been graded to smaller size fractions (e.g., < 12 mm) is one of the cheapest and most renewable substrate components for containerized crop production available in the U.S. Physical properties such as infiltration and hydraulic conductivity can vary widely depending on the particle size of the substrate. Understanding how varying size fractions affect physical properties can inform substrate selection and irrigation optimization in containerized cropping systems. This study aimed to investigate the physical properties and water dynamics of five different particle sizes of pine bark soilless substrates, <1 mm, 1-2 mm, 2-4 mm, 4-6 mm, and an unscreened fraction. To assess hydraulic conductivity, the particle size fractions of pine bark substrates were analyzed using a tension infiltrometer at four supply pressures, 0, -1, -3, and -5 cm. Hanging water column experiments were used to evaluate the water retention of the different particle sizes. Scanning electron microscopy was also used to qualitatively examine the differences in the surface structure of the pine bark particle sizes. The results revealed that smaller particle sizes exhibited significantly higher hydraulic conductivity, indicating faster water flow rates through the substrate. Substrates with smaller particle sizes also had higher water retention capacity. The smaller sized substrates also were observed to have greater water repellency than the larger particle sizes, however this was overcome in the first few minutes of wetting. Variations in particle shapes and sizes were seen for the different size fractions from the SEM data. These physical differences
contributed to the observed differences in hydraulic conductivity and water retention capacity i.e., the small pore sizes in the <1mm fraction controlled the higher rates of hydraulic conductivity. These findings suggest that substrates containing smaller particles may facilitate more efficient irrigation practices, allowing for better water distribution and uptake by plants. The information obtained from this study can assist nursery growers in making informed decisions regarding substrate selection and irrigation strategies, ultimately leading to more sustainable and efficient plant production practices.

3.1 Introduction

Containerized nursery production is used to cultivate a variety of plants, including woody ornamental crops, vegetables, floriculture, and fruit trees. Containerized production does have inherent challenges, however, especially in relation to water use. For example, pine bark, which has high porosity in the container, lowers plant-available water as compared to natural soils (Majsztrik et al., 2017). A typical grower response is to irrigate frequently, often multiple times per day. Applying water and fertilizer in excess is one solution for ensuring water availability to the plant. However, the excess leachate water can cause eutrophication of surface water and groundwater contamination if not properly managed. Practices to capture and reuse runoff from production do exist but have varying success and costs (Majsztrik et al., 2017).

Pine bark substrates are the substrate of choice for most growers in the U.S. (Carlile et al., 2015). Originally a byproduct of the timber industry, pine bark began to be used as a growing substrate in the 1970s. It rose in popularity due to its being easily available, lack of negative chemical constituents, and physical properties that are
favorable to plant growth, such as maintaining adequate air-filled porosity when in containers (Altland et al., 2018). However, pine bark is not suitable to be used as a growing medium in its original state. Pine bark that has been recently harvested must undergo physical and chemical changes (i.e., aging) to make it stable for use in growing plants (Kaderabek, 2017). The aging process typically relies on piles that are left in open-air conditions without any additions of fertilizer, lime, or water (Pokorny, 1975). Once aged and ready for distribution, pine bark can be sieved to different size fractions depending on customer specifications. Typically, pine bark is sieved between two sizes, smaller or larger than 6 mm (1/4 in). Then, the pine bark is usually amended with sand, perlite, peat, coir, or other soilless substrates, for a variety of reasons. Sand is most often added in the U.S. due to its low cost and availability, its ability to increase bulk density, and to keep the plants upright in wind and travel conditions. Sand also increases container capacity and tortuosity while lowering air space (Altland et al., 2018).

Cultivation methods that use pine bark help conserve natural resources, reduce industrial and regional agricultural wastes, and decrease transportation burdens compared to other substrates (Bilderback et al., 2013). However, having adequate understanding of the physical and hydraulic properties of pine bark and other soilless substrates is necessary to form best management practices for irrigation (Fields et al., 2020). This information is particularly important because water movement and storage in bark, as well as other substrates, are affected by the initial moisture content and subsequent infiltration patterns (Hoskins et al., 2014). Pine bark is known to be hydrophobic, and this phenomenon affects infiltration rates into the substrate. Physical mechanisms that affect the wettability of the substrate are non-uniform pore shapes, trapped air within the pores,
connectivity of the pores (Naasz et al., 2008). Past studies have utilized contact angle values to compare substrate wettability (Naasz et al., 2008; Paradelo et al., 2009). More recent work has explored the use of a correction term to model infiltration in water repellent media (Abou Najm et al., 2021).

Past studies have included particle size when describing properties such as air space, container capacity, and total porosity of substrate mixes (Pokorny, 1987; Zazirska et al., 2021). However, previous work has predominantly quantified physical and hydrologic properties of coarsely graded pine bark, e.g., ¼+ or ⅛- bark with and without amendments such as peat or coir, but has not explicitly focused on physical and hydraulic properties of screened fractions. There also is little knowledge of how different size fractions of pine bark substrates affect infiltration and water retention behaviors across a range of water contents. Our study sought to characterize how water movement and availability was affected by particle size of a pine bark substrate. We worked with four different size fractions (< 1 mm, 1-2 mm, 2-4 mm, and 4-6 mm) along with an unscreened control and described shape of the particles at each size fraction, measured infiltration, quantified water repellency and hydraulic conductivity, and characterized water retention. This information can be used to develop best management strategies for nursery growers to optimize water and fertilizer use and efficiency.

3.2 Methods

Sourcing substrates

Aged, stabilized pine bark substrate (≤ 12.7 mm) was obtained from Pacific Organics, Henderson, NC, USA. The bark was sifted using a Tyler Ro-tap shaker at the USDA ARS facility in Wooster, OH, U.S. into 5 particle size categories: unscreened, <1
mm, 1-2 mm, 2-4 mm, and 4-6 mm (Figure 3.1). Once separated, the substrates were brought to a mean moisture content (i.e., mass of water divided by mass of water plus substrate) of 57 ± 3.1% (mean ± standard deviation). Bulk density, air space, container capacity, total porosity, gravimetric water content, volumetric water content, and moisture content for each substrate were measured using porometers (Fonteno and Bilderback, 1993). Substrates were kept sealed in 18.9 L (5 gal) buckets at 7°C until the experiments began.

Figure 3.1. Pine bark substrates of 5 different particle sizes.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) was utilized to characterize particle size and shape. We used a HITACHI Tabletop Microscope (TM3000) to collect magnified images of the substrate. The substrate was placed on double-sided conducting sticky tape to hold the substrate to the plate. A fine layer of substrate was applied to the tape. The material
was placed in the SEM chamber and analyzed under a vacuum. We focused our scans on areas that emphasized particle size and shape in order to provide a qualitative depiction of the characteristics of the different bark size fractions.

**Non-equilibrium infiltration tests**

We conducted infiltration tests with a Mini-disk Tension Infiltrometer (METER Group, Pullman, WA, USA; see Figure 3.2). The substrates were packed to a constant bulk density of 0.15 g/cm$^3$ in 15.2 cm tall by 4.6 cm diameter clear polyethylene cores. For packing, two 10-cm long rubber couplings were attached to either side of the core. One coupling was capped with cheesecloth and the whole configuration was filled with substrate. Then, the unit was dropped off a 10 cm high surface onto a table three times. The upper coupling was filled to the top again and the process repeated until there was no change in the height of the substrate. The uncapped coupling was removed, the open end of the core was covered with a cap with five holes, each 0.32 cm in diameter, and a mesh screen was placed covering the holes. The core was inverted, and the other coupling was removed, leaving the upper surface of the core uncovered.

Once prepared, the core was attached to a ring stand with the infiltrometer placed atop. A layer of fine silica sand (250 μM) was placed on top of the substrate surface. The infiltrometer was set to the desired tension and then placed on the sand surface while ensuring a good hydraulic connection. We used three different tensions in this experiment: -5 cm, -3 cm, -1 cm, as well as runs with no tension (source pressure = 0 cm). The runs for the -3, -1, and 0 cm tensions lasted for 30 minutes or until the wetting front reached the bottom of the cores. The -5 cm runs were conducted for 4 hours in order
to achieve linear relationships between cumulative infiltration and time. Infiltration tests were run on each pine bark size fraction, with all samples having an initial volumetric water content (VWC) of 19 ± 5% (mean ± standard deviation). Additionally, we compared water content infiltrated at the -1 cm tension across particle sizes. This was a measure of how much water moved into the core before the wetting front reached the bottom of the core. Water content was measured as the volume of water infiltrated over the total volume of the core.

![Figure 3.2. Diagram of the infiltrometer experiment.](image)

**Figure 3.2.** Diagram of the infiltrometer experiment. The core of substrate is set under the infiltrometer with a layer of fine, silica sand in between.

**Water Repellency**

Pine bark substrates are known to be water repellent, especially when they begin to dry. We applied a water repellency model to the data to see if that was what was the cause of the unexpected increasing rate curve in the infiltration data. A comparison of the
water repellency of the five particle sizes was completed using data from the infiltrometer tests. We used the -1 cm and -3 cm tests in these comparisons, since the water repellency was most evident under those tensions. The infiltration data was corrected for water repellency using Equation 3.

**Equilibrium water content characterization**

Tempe pressure cells (SoilMoisture Equipment Corp., Santa Barbara, CA, USA) were connected to a hanging water column device to determine water retention properties during drainage (Figure 3.3). Each tempe cell held a cylindrical sample ring that was 5.08 cm in diameter and 2.54 cm in height. The hanging water column was created with a 150-cm tall wooden structure that had a Mariotte water supply set so the water level was even with the top of the tempe cells and water could enter the bottom of the cores (saturating them from below). We connected the drainage line of the tempe cells to a hanging tube that had outlet lines located at heights of 5 cm, 10 cm, 15 cm, 25 cm, 50 cm, and 100 cm. The setup could accommodate six tempe cells at the same time. As the water is held under different tensions, the ability for plants to access this water changes. As such, we categorized four pools of water availability under these six tensions. Air volume at container capacity (AV) was considered to be 0 to -10 cm, easily available water (EAW) was -10 to -50 cm, water buffering capacity (WBC) was -50 to -100 cm, and unavailable water (UAW) was considered to be < -100 cm (Caron and Michel, 2021).

Packing of the cores took place on top of the structure with the tempe cells already connected to the drainage tubes. To ensure consistent packing, each core was tapped 3 times against the wood of the structure after each spoonful of substrate. The
cores were saturated from the Mariotte bottle, a process that took around 40 minutes. Once the substrates were completely saturated, the inlet tubes were closed, and the highest (5 cm) outlet tubes were opened. Water that drained from the outlet line was collected in a covered container and weighed after 2 hours to determine change in water content of each sample. After weighing, the collected water was discarded, the outlet line was closed, and the next lowest outlet line was opened. This process was repeated for each drainage elevation. We also had two flasks that were filled with water but not connected to a core. These containers were used to correct for any evaporation that occurred during the 2-hour drainage period. We ran the tempe cell experiment 3 times for each substrate particle size. These data were used to create moisture characteristic curves and quantify which pores drained under each tension.

Figure 3.3. The hanging water column set up. Substrated-filled tempe cells drained into Erlenmeyer flasks to determine change in water content at increasing tensions.
Analysis

The hydraulic conductivity associated with each source tension, \( K(h_{\text{source}}) \), was estimated from the mini-disk infiltrometers by assuming that infiltration had reached steady-state conditions by the end of the test:

\[
I(h_{\text{source}}) = K(h_{\text{source}}) \cdot t + c
\]

where \( I(h_{\text{source}}) \) is the cumulative infiltration for each test, \( t \) is the elapsed time, and \( c \) is a constant. \( K(h_{\text{source}}) \) and \( c \) were determined by applying linear regression to the final 4-10 observations of \( I(h_{\text{source}}) \) and \( t \).

The four different \( K \) values were then fit using least-squares regression to the Brooks and Corey (1964) model:

\[
K(h_{\text{source}}) = K_s \quad h \geq h_b
\]

\[
K(h_{\text{source}}) = K_s \left( \frac{h_b}{h_{\text{source}}} \right)^\eta \quad h < h_b
\]

where \( h_b \) is the bubbling pressure \( (h_b < 0) \) and \( \eta \) is a parameter related to the pore size distribution \( (\eta > 2) \).

A comparison of the water repellency of the five particle sizes was also completed using data from the infiltrometer tests. The cumulative infiltration accounting for water repellency, \( I_{wr} \) was described using the model of Abou Najm et al. (2021):

\[
I_{WR}(t) = c_1 \sqrt{t} - \frac{c_1 \sqrt{\pi}}{2 \sqrt{a_{WR}}} \text{erf} \left( \sqrt{a_{WR} t} \right) + c_2 t - \frac{c_2 (1 - e^{-a_{WR} t})}{a_{WR}}
\]

Where \( c_1 \) and \( c_2 \) are constants specific to initial and boundary conditions, and \( a_{WR} \) is an empirical soil parameter that describes the reduction rate of the infiltration rate of the substrate. We used the -1 cm and -3 cm tests in these comparisons, since the water repellency was most evident under those tensions. We determined best-fit values for \( c_1 \),
c_2, and \( \alpha_{WR} \) for each test using least-squares regression with the evolutionary algorithm in the Microsoft Excel solver. We then compared \( \alpha_{WR} \) of the five particle sizes to determine the relative water repellency of each.

**Statistical Analysis**

Regression analyses were completed on the infiltration and hanging water column data. The observed \( K \) values and water contents were compared against the median particle size to perform a regression analysis. JMP Pro 16 was used to perform all the statistics.

**3.3 Results and Discussion**

**Porometer Data**

The smallest size fraction (<1 mm) had the least amount of air space, the highest container capacity, highest total porosity, and largest bulk density in comparison to all the particle sizes (Table 3.1). The sizes containing the smallest particle sizes (i.e., <1 mm, 1-2 mm, and unscreened) had the largest corresponding container capacity or maximum amount of water the material can hold. The largest particle sizes (2-4 mm and 4-6 mm) had the largest amount of air space and the lowest bulk densities.
Table 3.1 Static physical properties of the five pine bark particle sizes from porometer data. Data collected by Hannah Blice, USDA ARS, Wooster, OH.

<table>
<thead>
<tr>
<th>Particle size</th>
<th>Percent solid (cm$^3$/cm$^3$)</th>
<th>Air space at container capacity (cm$^3$/cm$^3$)</th>
<th>Container capacity (cm$^3$/cm$^3$)</th>
<th>Total porosity (cm$^3$/cm$^3$)</th>
<th>Bulk density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unscreened</td>
<td>0.25</td>
<td>0.30</td>
<td>0.46</td>
<td>0.78</td>
<td>0.16</td>
</tr>
<tr>
<td>&lt;1mm</td>
<td>0.19</td>
<td>0.05</td>
<td>0.75</td>
<td>0.80</td>
<td>0.19</td>
</tr>
<tr>
<td>1-2mm</td>
<td>0.17</td>
<td>0.28</td>
<td>0.50</td>
<td>0.78</td>
<td>0.14</td>
</tr>
<tr>
<td>2-4mm</td>
<td>0.30</td>
<td>0.41</td>
<td>0.32</td>
<td>0.73</td>
<td>0.13</td>
</tr>
<tr>
<td>4-6mm</td>
<td>0.19</td>
<td>0.53</td>
<td>0.27</td>
<td>0.79</td>
<td>0.12</td>
</tr>
</tbody>
</table>

**Scanning Electron Microscopy (SEM)**

The images collected with the SEM of the five substrate sizes showed a variety of particle shapes and sizes (Figure 3.4). The unscreened pine bark particles contained many elongated and rectangular particles of different sizes. The larger pieces had rough, rounded edges and the smaller were rounded and less rectangular. The <1 mm size had more particles per unit area; this greater surface area likely allowed for greater adsorbed water. The pieces varied from rounded and almost circular to long, thin, and rectangular. The 1-2 mm fraction showed a variety of different particle sizes and thicknesses and were predominately rectangular in shape with rough, rounded edges. The 2-4 mm particle size contained large, thick pieces of pine bark and whole pieces could not be captured in one frame. Finally, the 4-6.3 mm particle size contained the largest bark fragments along with a variety of smaller sizes. These pieces appeared to have less surface topography than the
other particle sizes. All images revealed large (>1 mm) pore spaces between particles; these spaces were too large to hold water via capillary attraction. Also note that all images showed light-colored areas on the substrates, which represented metals (likely iron oxides) adsorbed to the organic matter.

Figure 3.4. SEM images of A. unscreened pine bark at 30x magnification, B. <1 mm particles at 40x magnification, C. 1-2 mm at 30x magnification, D. 2-4 mm at 40x magnification, and E. 4-6 mm at 30x magnification pine bark substrate. Scale=2mm.

Infiltration Data

The data collected from the tension infiltrometers revealed that $K_s$ was inversely proportional to particle size. As particle size increased, hydraulic conductivity decreased, with the $K_s$ for unscreened size fraction falling between 2-4 mm and 4-6 mm (Figure 3.5). The smallest particle size, <1 mm, also had the largest overall $K(h_{source})$ values at each tension, while the largest size, 4-6 mm, had the smallest $K(h_{source})$ values at
each tension. The two middle sizes (1-2 mm and 2-4 mm) had intermediate $K$ values, with 1-2 mm having greater $K$ values than 2-4 mm for all source pressures except $h = -3$ cm. The unscreened size fraction had similar $K$ values as the 1-2 mm size fraction. As observed, the smaller particle sizes allowed for higher $K$ values than the larger sizes. This information can inform growers to select smaller particle sizes to increase water movement into and through substrates. Alternatively, smaller sizes maybe used at least on the upper half of a container to increase $K$ and increase water movement into the container.

The Brooks and Corey model (Equation 2) closely match the $K$ values calculated when $h_{source} \geq -3$ m (Figure 3.5) but did not fit the $K$ values measured at the highest tension (-5 cm). Specifically, the modeled $K$ values were much higher than the measured ones in all but the unscreened substrate. We attribute this discrepancy to the relatively narrow pore size distributions in each of the screened particles. As tension increased, the substrate had fewer connected pores present and more “dead end” pores, resulting in a lower-than-expected $K$. 


Figure 3.5. Hydraulic conductivity, $K(h)$, of the five substrates measured at saturation and three source tensions ($h = -1, -3,$ and $-5$ cm). Points refer to values measured from infiltration tests at different source pressures; solid lines indicate extrapolated data using the Brooks and Corey (1964) model, Eq. (2).

Regression analyses were run for the particle sizes versus $K$ at each tension. There was no significant relationship seen for tensions $-1, -3,$ and $-5$ (Figure 3.6). There was a significant relationship between particle size and $K$ for the 0 tension ($R^2=0.97$). There were strong correlations between particle size and $K$ for the other tensions as evidenced by their large $R^2$ values (i.e., $-1$: $R^2= 0.73$, $-3$: $R^2= 0.57$, and $-5$: $R^2= 0.76$). Overall, particle size was shown to have an influence over $K$, especially at low tension.
Water repellency was most evident in the infiltration tests for the -1 and -3 cm tensions across all particle sizes. The rate of infiltration over time was increasing over time instead of displaying a linear trend line as expected (data not shown). In order to compare water repellency between substrate particle sizes, $\alpha_{wr}$ values were calculated by fitting the infiltration measurements with Equation (3) and were then compared for each of the sizes (Figure 3.7). Note that the smaller $\alpha_{wr}$ values indicate greater effects from water repellency on the substrate. When comparing the two applied tensions, $\alpha_{wr}$ values tended to be smaller for the -1 cm runs as compared to the -3 cm runs. As tension
decreases, larger pore sizes are activated. This data would suggest the larger pore sizes are potentially more water repellent than the smaller pore sizes. As an overall trend seen when comparing the five particle sizes, the relationship between particle size and $\alpha_{wr}$ tended to be positively correlated, the exception being the 4-6 mm substrate in the -1 cm run.

The results of this test were compared using a two-way ANOVA to compare the effects of particle size and tension on $\alpha_{wr}$. Tukey HSD was the post hoc test applied to particle size and the tensions were compared using a student’s t-test. There were no significant differences seen in the relationships of $\alpha_{wr}$ to particle size or tension.

![Figure 3.7. Comparison of $\alpha_{wr}$ values for each particle size. The water repellency model was fit to the -1 and -3 cm tensions. The smaller the $\alpha_{wr}$ value the greater the water repellency.](image)
The greatest amount of water infiltrated through the unscreened and <1mm sizes and the least through the 2-4 mm and 4-6 mm fractions (Figure 3.8). A one-way ANOVA was used to compare change in VWC and particle size, then a Tukey HSD post hoc test was applied. No significant differences were seen. However, overall wettability trends were witnessed.

The smaller particle sizes had a more uniform flow rate through the core, allowing for a greater volume of water to flow through before the bottom of the core was reached. In contrast, the larger particle sizes displayed a more preferential flow path. The water tended to follow specific paths through the core and a smaller volume of water was able to infiltrate before the water reached the bottom of the core. Also, the pores in the larger particle sizes were likely not fully filled due to this preferential flow path.

Figure 3.8. Change in volumetric water content (ΔVWC) for each particle size. This figure is a comparison of water infiltrated before the wetting front reached the
bottom of the core for the -1 cm tension runs. Bars represent the mean values and error bars indicate the standard error of the mean.

Overall, the smaller particles appear to be more important for maintaining large $K$ values than larger particle sizes. The smaller size fractions were shown to have had better connectivity between smaller pores and therefore had the highest $K$ under tension conditions. It also was seen that the smaller pores become more filled with water as opposed to trapped air than the larger pores. This is evidenced by the uniform wetting front observed in the smaller particle sizes. Additionally, the smaller pore sizes were viewed to have decreased rates of water repellency as compared to the larger pore sizes, while the smaller particle sizes had increased water repellency in contrast to the larger particle sizes.

**Hanging Water Column**

The different substrate particle sizes had a range of total porosities, ranging from $\phi = 0.57 – 0.75 \, \text{cm}^3 \, \text{cm}^{-3}$. However, the substrates had distinct water retention curves (Figure 3.9). The second smallest size fraction (1-2 mm) had the greatest amount of water held over the tension range of 0 to -100 cm. The smallest size (<1 mm) held onto the next most water, even though its initial saturated water content is smaller than all but the 4-6 mm fraction. These findings emphasize the results from the porometer data of the small size fractions having the largest container capacity. The other sizes decreased in water retention with increasing particle size; with the unscreened fraction falling between the two largest fractions (2-4 mm and 4-6 mm).
Through the AV, EAW, and WBC the 1-2 mm size fraction held on to the most water during drainage, with $\theta = 0.57 \text{ cm}^3 \text{ cm}^{-3}$ at $h = -100 \text{ cm}$, with the <1 mm size coming in at a close second with $\theta = 0.46 \text{ cm}^3 \text{ cm}^{-3}$ at $h = -100 \text{ cm}$. Interestingly, the unscreened fraction had the third greatest water retention at the greatest tension, with $\theta = 0.40 \text{ cm}^3 \text{ cm}^{-3}$ at $h = -100 \text{ cm}$. The middle-sized fraction, 2-4 mm, held onto the second least amount of water, with $\theta = 0.39 \text{ cm}^3 \text{ cm}^{-3}$ at $h = -100 \text{ cm}$. Finally, the 4-6 mm fraction held the least amount of water overall, $\theta = 0.37 \text{ cm}^3 \text{ cm}^{-3}$ at $h = -100 \text{ cm}$. The regression analysis (Figure 3.10) did not show a significant relationship between particle size and hydraulic conductivity.

![Water retention curves for the five substrate size fractions based on drainage experiments. Each point represents the mean of at least 3 samples. The arrows represent the three pools of water availability: air volume at container capacity (AV), easily available water (EAW), and water buffering capacity (WBC).](image-url)

Figure 3.9. Water retention curves for the five substrate size fractions based on drainage experiments. Each point represents the mean of at least 3 samples. The arrows represent the three pools of water availability: air volume at container capacity (AV), easily available water (EAW), and water buffering capacity (WBC).
Figure 3.10. Regression analysis of median particle size vs. water content. The regressions were divided by the three pools of water availability: air volume at container capacity (AV), easily available water (EAW), and water buffering capacity (WBC).

The results from both the hanging water column experiment and the infiltration-based experiment show that the smallest size fraction (<1 mm) had the best water retention and $K$ of the size fractions. This aligns with the data from the porometers, which showed that the smallest sizes had the largest container capacity and porosity. The largest amount of water is able to be stored in the smallest two fractions and they also retain the greatest volume under tension. Additionally, the unscreened particle size did not perform well and was not seen to maximize the benefits of both the small and large fractions. The
mixed particle size does improve hydraulic conductivity relative to the 4-6 mm fraction, but it does not improve water retention characteristics. The unscreened fraction had the least loosely bound water (AV and EAW) as compared to the other particle sizes.

3.4 Conclusions and Implications

Characterizations of the physical properties of pine bark substrates have been completed broadly, however, there is a lack of data on the properties of different particle sizes and of pine bark substrates without amendments. Measurement of characteristics that influence how water moves into, through, and out of a substrate container can inform and potentially improve current practices for the optimal water use and production costs. To address this gap in knowledge, we utilized three methods for the description of physical properties of pine bark soilless substrates: SEM, infiltrometers, and hanging water columns.

Results show that SEM provided qualitative insights into particle size and shape, revealing rough surfaces and large pore spaces between particles, as well as differences in surface area that contribute to water holding capacity. During the non-equilibrium tests using a tension infiltrometer, we found that the smaller size fractions had higher $K$ values and the unscreened size fraction was most similar to the intermediate sized particles (1-2- and 2-4-mm sizes). Non-equilibrium infiltration tests using a tension infiltrometer showed that $K(h)$ decreased with increasing particle size. The smallest particle size fraction (<1 mm) exhibited the highest $K$ values at each tension, while the largest fraction (4-6 mm) had the lowest $K$ values. Smaller particle sizes demonstrated better connectivity between pores, leading to higher $K$ values under tension conditions. This was most likely
due to the connectivity of the pores, the smaller pore sizes, and the ability of the smaller sizes to hold more water as seen by the porometer data.

For the equilibrium experiment, moisture characteristic curves were generated to understand water retention properties during drainage. The two smallest size fractions performed best, followed closely by the largest size fraction in all of the water availability pools. These results suggest that pores of the pine bark substrate that are greater than 2 mm are so large that the water retention characteristics are not greatly influenced by the screened variety in particle size. The unscreened size fraction characteristics usually fit more closely to the 2-4 mm particle size. Therefore, the addition of smaller particle sizes to a large particle size improved $K$ as compared to the 4-6 mm but did not seem to improve the water retention characteristics.

Overall, our study contributes valuable information on the physical and hydraulic properties of different size fractions of pine bark substrates. Stratified systems are a new system of potting that packs large size fractions in the bottom and smaller sizes on the top. Studies have shown these systems can optimize water retention in the top half of the container and drainage and air flow in the bottom half of the container. In a comparison against conventional bark substrate, plants grown in stratified containers had better survival rates, mitigation against water stress, and improved crop growth and yield (Criscione et al., 2022). From the data collected in this study, stratified systems could be implemented using the <2 mm size fractions on the upper part of a container and having the lower portion be filled with 2-4 mm to prevent water logging and promote air permeability. The knowledge from this study can further assist nursery growers in optimizing water usage, thereby improving resource efficiency. By making informed
decisions regarding pine bark substrate mixes, producers can implement best
management strategies for sustainable nursery production.
4. Gas Diffusion Characteristics of Pine Bark Substrates: Effects of Particle Size and Moisture Levels

Abstract

Adequate access to oxygen within the growing media plays a crucial role in plant production via plant root respiration. This study aimed to investigate the gas diffusion characteristics of pine bark substrates under different particle sizes and moisture conditions. Five particle size categories, <1 mm, 1-2 mm, 2-4 mm, 4-6 mm, and an unscreened fraction, were compared under four different initial moisture contents: an initial volumetric water content (VWC) of 18 ± 4% (mean ± standard deviation), unsaturated wetting to 22 ± 4% VWC, partially saturated wetting to 27 ± 8% VWC, and drainage from saturation to 48 ± 18% VWC. Gas diffusion coefficients ($D_s$) were determined and compared using a one-chamber gas diffusion setup. Results indicated that the smaller particle sizes exhibited a significant decrease in $D_s$ as moisture content increased, while the larger particle sizes showed minimal sensitivity to wetness. Pores in coarser substrates were large enough that they negated the effect of moisture on gas diffusion, since they likely maintained connected air-filled porosity under all of the tested moisture contents. A two-way ANOVA confirmed that interactions between particle size and wetness significantly affected $D_s$. Additionally, the analysis revealed significant differences between the smallest (<1 mm, 1-2 mm) and larger particle sizes (2-4 mm, 4-6 mm, unscreened), as well as between initial conditions and drainage conditions. Measurement of gas diffusion for different pine bark particle sizes can be applied to
optimize substrate mixes or create stratified containers based on water retention and gas diffusion data to enhance irrigation strategies and plant growth.

4.1 Introduction

The exchange of gas between the atmosphere and growing media such as soil and substrates is an important process for plant root respiration, survival of micro and macro soil organisms, production of greenhouse gasses and other essential processes (Allaire et al., 2008; Stępniewski et al., 2011). Gas exchange between soil and the atmosphere is influenced by in a number of physical, chemical and biological processes.

Oxygen, carbon dioxide, and nitrogen are the most prevalent gasses in the pore spaces of growing media such as soilless substrates (Stępniewski et al., 2011; Allaire et al., 1994). Carbon dioxide is produced by oxic respiration of plant roots, soil microorganisms, and meso- and macrofauna, as well as by anoxic respiration and fermentation by microbes. Nitrogen is the most abundant gas in the soil medium, just as it is aboveground. It moves into and out of the soil via diffusion and mass flow for fixation and denitrification to provide nutrients that are important for plant dynamics. However, within the soil medium, oxygen is the most important gas. It is a major factor in biochemical and chemical reactions in the soil and it is vital for plant root respiration (Stępniewski et al., 2011). Adequate rates of exchange between CO₂ and O₂ are important to ensure successful plant growth. Restricted gas diffusion halts growth and impedes start and distribution of new roots (Allaire et al., 1994).

Aeration problems are a common problem that growers combat with soilless media (Allaire et al., 1996). Pine bark substrates are the favored organic growing media
in many parts of the United States and are regarded as having excellent air permeability (Carlile et al., 2015). However, they are also known to have decreased water holding capacity as compared to other substrate mixes (Altland et al., 2018). The media must be well-drained to avoid the “container effect” in which the gravitational drainage cannot overcome matric potentials and water is held within pores. However, once this problem has been overcome, the containers often require excess irrigation to avoid water stress on the plants (Fields et al., 2020).

The two fundamental mechanisms of gas exchange within the soil matrix are advection and molecular diffusion. Advection is movement controlled by pressure gradients created by temperature changes, water infiltration, and other natural variability (Stępniewski et al., 2011). Diffusion is the primary exchange of gas between soils and the atmosphere (Xu et al., 1992). The diffusion coefficient, $D_s$, describes the rate at which a gas moves given a particular concentration gradient, and is the primary way to characterize gas diffusion properties of porous media (Allaire et al., 2008).

The $D_s$ coefficient is determined by the air-filled pores and the way that these pores are distributed, connected, and the tortuosity of the connections (Allaire et al., 1996). These factors are influenced by the arrangement of the soil or substrate particles and the bulk density of the medium (Stępniewski et al., 2011). Other factors which affect gas diffusivity include container geometry, potting procedures, root activity, and shrinkage of the media (Caron and Nkongolo, 2004). Two factors that can be altered are choice of substrate particle size and water content of the substrate.

There are a variety of methods for analyzing gas diffusivity of soil cores. The study previously mentioned (Caron and Nkongolo, 2004) took gas diffusion
measurements three ways: gas diffusion calculated from $N_2$ movement through a core, diffusivity from the water desorption curve and saturates hydraulic conductivity, and air entry values. A comparison of methodology (Allaire et al., 2008), reported on five methods for measuring gas diffusion characteristics of soil samples, including utilizing intact cores, closed systems, repacking columns, and other varieties in methods. These measurements can be conducted using one-chamber or two-chamber systems (Schjønning et al., 2013).

Previous studies on gas exchange of growing media have focused on the addition of large particles to increase aeration. Caron et al. 2005 looked at 13 different substrate types and found that gas diffusivity was highest for the finest fraction (2-4 mm) fraction and that adding increasingly coarse material decreased gas diffusivity. That work contained three bark and peat mixes but only considered fine and coarse size fractions (Caron et al., 2005). Another study by Caron and Nkongolo (2004), examined peat amended with pine bark of four different size fractions and saw similar effects of decreasing gas diffusion with increasing particle size. However, neither of these studies varied water content, which is needed to understand dynamic gas diffusion processes. Moreover, no study has yet considered gas diffusion in substrates with an imposed moisture gradient, even though water contents decrease as a function of elevation in nursery containers that are being actively watered and allowed to dry.

For this study, we used a one-chamber system with repacked cores to be able to compare bulk densities of the cores. Additionally, this study varied moisture levels of the substrates. The known complications concerning the balance of water and air within pores necessitated this study. We also wanted to understand the conditions of a container
after it has been irrigated and began to dry. There is a variety of moisture levels within the containers themselves. In order to understand this gradient, we needed to find a way to mimic these conditions. This study seeks to categorize the gas diffusivity of pine bark under varying particle size and wetness conditions by determining and comparing the gas diffusion coefficients.

4.2 Methods

Treatments

Two treatments were applied in this experiment: 1) particle size, and 2) moisture content. Aged, stabilized pine bark was sifted into 4 categories based on particle size: <1 mm, 1-2 mm, 2-4 mm, and 4-6 mm. An unscreened blend of the sizes was also analyzed. The source and porometer characterization of the substrate materials is described in Chapter 3.2.

The substrates were placed into 5 cm diameter by 5 cm tall cores that had a 0.25 mm screen attached to the bottom. Cores were packed by spooning loose substrate tapping the bottom three times after every spoonful of substrate. The substrate was prepared one of the following ways before being attached: a uniform volumetric water content (VWC) based on the initial wetness of 18 ± 4% (mean ± standard deviation), unsaturated wetting to 22 ± 4% VWC, partially saturated wetting to 27 ± 8% VWC, and drainage from saturation to 48 ± 18% VWC (Table 4.1).
Table 4.1. Comparison of volumetric water contents by particle size, displaying the variability between the smallest and largest sizes, n= 3.

<table>
<thead>
<tr>
<th></th>
<th>Non-wetted</th>
<th>Unsaturated Wetting</th>
<th>Partially Saturated Wetting</th>
<th>Drainage from Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1mm</td>
<td>16.5</td>
<td>25.9</td>
<td>34.8</td>
<td>73.9</td>
</tr>
<tr>
<td>1-2mm</td>
<td>14.8</td>
<td>20.1</td>
<td>28.1</td>
<td>58.0</td>
</tr>
<tr>
<td>2-4mm</td>
<td>17.1</td>
<td>17.9</td>
<td>19.8</td>
<td>39.8</td>
</tr>
<tr>
<td>4-6mm</td>
<td>15.6</td>
<td>19.0</td>
<td>18.9</td>
<td>28.8</td>
</tr>
<tr>
<td>Unscreened</td>
<td>24.5</td>
<td>24.9</td>
<td>35.4</td>
<td>41.8</td>
</tr>
<tr>
<td>Average</td>
<td>17.7</td>
<td>21.6</td>
<td>27.4</td>
<td>48.5</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3.9</td>
<td>3.6</td>
<td>7.9</td>
<td>17.6</td>
</tr>
</tbody>
</table>

The non-wetted cores put straight on the gas diffusion chamber. The drainage cores were soaked for an hour in water, repacked to the top (Table 4.2), soaked again for 30 minutes, and then allowed to drain for 30 minutes before attaching to the gas diffusion chambers. We established the unsaturated wetting and the partially saturated wetting conditions using a minidisk infiltrometer. The cores were packed and the minidisk infiltrometers (METER Group, Pullman, WA, USA) were placed on top at -5 cm or -7 cm tension and left to infiltrate overnight (i.e., at least 12 hours). This process created a pressure gradient within the core (Figure 4.1) (Figure 4.2) that was intended to mimic equilibrium conditions in a growing container after relatively low-intensity versus high-intensity watering events.
Table 4.2. Comparison of bulk densities (g/cm$^3$) for each particle size before and after repacking for the drainage from saturation treatment.

<table>
<thead>
<tr>
<th>Size</th>
<th>Original $\rho_b$</th>
<th>Repacked $\rho_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1 mm</td>
<td>0.15</td>
<td>0.19</td>
</tr>
<tr>
<td>1-2 mm</td>
<td>0.13</td>
<td>0.16</td>
</tr>
<tr>
<td>2-4 mm</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>4-6 mm</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Unscreened</td>
<td>0.14</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Figure 4.1. The pressure gradient set up, in which a core is packed with substrate and a tension infiltrometer is set on top. Water moves down into the substrate until coming to equilibrium, at which time a moisture gradient exists vertically through the core that mimics real-world conditions in a nursery container.
Figure 4.2. Comparisons of the VWC and the elevation in core for the four water contents.

**Gas diffusion chamber**

The one chamber set-up used for this study (Allaire et al., 2008) consisted of two large PVC pipes attached to Apogee 210 oxygen sensors at one end of the pipe and the other end was connected to a soil core via rubber couplings and open to the atmosphere (Figure 4.3). Fans were attached to either end of the chambers to ensure even mixing. The PVC was sealed with PVC sealant as well as an additional silicone coating to the outside of all points of possible leakage. The rubber couplings were coated in vacuum grease on the inside at the interface with the PVC pipe to ensure no air leakage.
Figure 4.3. The one-chamber gas diffusion device used to determine the gas diffusion coefficient, $D_s$.

The oxygen sensors were connected to a datalogger (CR1000 Campbell Scientific, Inc., Logan, UT, U.S.), which took readings every 30 seconds. To start the procedure, the chambers were flushed with nitrogen gas to ensure an oxygen-free environment. The chamber was connected to the N$_2$ gas cylinder at the back end near the oxygen sensor and was run for one to two minutes until the readings were $<0.3$ mV. Then, the tubing which the N$_2$ gas was entering was clamped shut and the core of substrate was attached to the opposite end. Cores were run for one hour. Temperature in the room varied from 20°C to 24°C.
Analysis

Fick’s first law for one-dimensional gas diffusion is:

\[
f_g A = \frac{d m_g}{d t} = -D_s \frac{d C_g}{d x} A
\]

(1)

where \(f_g\) is the gas flux density [M L^{-2} t^{-1}], \(m_g\) is the amount of gas diffusing [M], \(A\) is the cross-sectional area of the soil core [L^2], \(D_s\) is the soil gas diffusion coefficient [L^2 t^{-1}], \(C_g\) is the gas concentration [M L^{-3}], and \(x\) is distance [L]. The mass of gas in the chamber is found by:

\[
m_g = C_g V
\]

(2)

where \(V\) [L^3] is volume of chamber. Substituting Equation 2 into Equation 1 gives:

\[
\frac{d C_g}{d t} = -\left(\frac{D_s A}{V}\right) \frac{d C_g}{d x}
\]

(3)

An approximation of the concentration gradient \(\frac{d C_g}{d x}\) can be written as \((C_g - C_s)/L\), where \(L\) is the length of the core and \(C_s\) is concentration under atmospheric conditions at the core edge [M L^{-3}]. Substituting this approximation into Equation (3) and integrating leads to:

\[
\ln C_r = -\frac{D_s A t}{VL} = at
\]

(4)

where \(C_r = (C_g - C_s)/(C_0 - C_s)\), \(C_0\) is the initial gas concentration in the chamber [M L^{-3}], and \(a\) is the slope of the regression line between \(\ln(C_r)\) and \(t\).

Equation (4) can be rearranged to find the gas diffusion coefficient \(D_s\):

\[
D_s = -\frac{a VL}{A}
\]

(5)

To use Equation (5), we calculated \(C_r\) from the oxygen concentrations measured between 0.25 and 0.75 hours, and then found the slope of the regression line \((a)\) between \(\ln(C_r)\) and \(t\). The \(D_s\) coefficient was measured a minimum of three times for each combination of particle size and water content.
Statistical Analysis

To determine whether particle size and substrate water content influenced $D_s$, a two-way ANOVA was run using the software package JMP Pro 16 (alpha = 0.05). A post-hoc Tukey HSD was also run for both factors to identify any specific differences between means (Dane and Topp, 2002). A Dunnett test was run to see differences between the four particle sizes and the unscreened fraction, which was considered to represent the control in this analysis.

4.3 Results and Discussion

Porometer data

The data from the porometers (presented in Chapter 3) that is most important for this chapter is the comparison of percent air space. The smallest two size fractions had the smallest amount of air space, with <1 mm having an order of magnitude smaller percentage than all the other sizes (Table 3.1). The 2-4 mm and 4-6 mm had the largest amounts of air space with 41.1% and 52.5%, respectively. The unscreened fraction has the median amount of air space closest to the 1-2 mm size, so it is more controlled by the large pore spaces than the smaller particle size filling in between the large. Porometer data only relates to the drainage after saturation water content. All data from the porometer is considered at container capacity like the drainage measurement.

Gas diffusion data

Gas diffusion coefficient $D_s$ decreased as water content increased for most of the particle sizes (Figure 4.4). However, the 2-4 mm and the 4-6 mm did not display this
trend. The $D_s$ values for these two sizes did not vary more than 5% from the value obtained from the non-wetted sample (18% VWC). In contrast, for <1 mm, $D_s$ ranged from 0.0041 m$^2$/s under the non-wetted condition to 0.0008 m$^2$/s in the drained sample, nearly an order of magnitude difference. These data suggest that large particle sizes likely had sufficient space for airflow that the wetness of the material did not affect gas exchange. Specifically, the large pore spaces of those size fractions were unable to fully fill and hold water and therefore did not impact air flow. For the smaller particle sizes, a larger proportion of pores were able to fill with water and restrict airflow. The larger particle sizes and the unscreened fraction also had the highest values of $D_s$, another display of the large pores allowing the most airflow.

A Dunnett test was run to compare the four screened fractions to the unscreened fraction as a control (Figure 4.4). The two smallest sizes (<1 mm and 1-2 mm) were seen to be significantly different than the unscreened fraction. The two larger fractions (2-4 mm and 4-6 mm) were not significantly different. Therefore, the unscreened fraction appears to have large drainable pores even though it contains a mix of small and large particles. The smaller particles would be expected to fill in between the larger pores, especially since the unscreened fraction has a bulk density most like the <1 mm size fraction. However, it seems that the unscreened fraction is able to maintain large pore spaces to allow for gas diffusion similar to the larger sizes.
Figure 4.4. Gas diffusion coefficients ($D_s$) measured for different particle sizes (horizontal axis) and for four water contents (rows). Asterisks indicate significant differences from the control (Dunnett test; $p < 0.05$).

A two-way ANOVA was run to compare the four screened particle sizes and the four wetness conditions (Figure 4.5). The ANOVA was shown to be significant ($p < 0.0001$, $R^2 = 0.72$). The model also showed that both particle size, wetness, and their interaction had significant effects on $D_s$. The two smallest particle sizes, <1 mm and 1-2 mm, were significantly different from the two larger particle sizes, 2-4 mm and 4-6 mm. The non-wetted and drainage from saturation were the two wetness effects that were significantly different from one another. A regression analysis was also run comparing $D_s$ and median particle size (Figure 4.6). The larger particle sizes were shown to have higher
$D_s$ values and the opposite is true for the smaller sizes. The results were strongly influenced by water content, which played a strong role in the effects seen.

![Figure 4.5](image.png)

**Figure 4.5.** Two-way ANOVA comparing $D_s$ values against the four moisture contents and four particle sizes. The cores were prepared one of the following ways before being analyzed: an initial, non-wetted volumetric water content (VWC) of $18 \pm 4\%$ (mean $\pm$ standard deviation), an unsaturated wetting core of $22 \pm 4\%$ VWC, a partially saturated wetting core of $27 \pm 8\%$ VWC, and a drainage from saturation core of $48 \pm 18\%$ VWC. Different letters indicate significant difference.
Figure 4.6. Regression analysis of diffusion coefficient ($D_s$) versus median particle size; the different lines represent the different water contents. The cores were prepared one of the following ways before being analyzed: an initial, non-wetted volumetric water content (VWC) of 18 ± 4% (mean ± standard deviation), an unsaturated wetting core of 22 ± 4% VWC, a partially saturated wetting core of 27 ± 8% VWC, and a drainage from saturation core of 48 ± 18% VWC.

The results seen from this experiment show that the larger particle sizes have more connected air space and allow better air permeability. The smaller two sizes were shown to have less air permeability and be more affected by moisture content. However, as in the results from Chapter 3, the large particle sizes were shown to have lower hydraulic conductivity ($K$) and less water retention. In contrast, the smaller particle sizes
displayed higher rates of $K$ and greater water retention but were more affected by moisture content. These results imply that the implementation of a stratified system could be beneficial. Criscione et al 2022 states that stratified systems likely improve aeration of the potting system. The results from this current study suggests that a stratified system of $<1$-$2$ mm pine bark over $2$-$6$ mm pine bark would allow for a mix of these favorable properties. The upper layer would increase water retention and possibly allow for less frequent irrigation, while the roots of the plants would still be able to receive adequate aeration from the well-drained layer on the bottom.

4.4 Conclusions and Implications

This study focused on characterizing the air diffusivity of pine bark substrates with different particle sizes. We employed a one-chamber gas diffusion setup to measure oxygen concentrations and solved for the gas diffusion coefficient ($D_s$) of pine bark substrates against two variables: particle size and moisture content. The results demonstrated an overall trend of decreasing $D_s$ with increasing substrate water content for most particle sizes. However, the larger particle sizes showed less sensitivity to wetness due to their large pore spaces. The statistical analysis confirmed that both particle size and moisture level had a significant effect on $D_s$. These findings highlight the importance of considering particle size and moisture levels when making decisions about substrate mixes or stratified containers in growing systems. By understanding the relationships between particle size, wetness, and gas diffusivity, growers can make informed decisions to enhance aeration and promote optimal plant growth. Further
research in this area can continue to refine substrate engineering and cultivation strategies
to maximize plant health and productivity.
5. Conclusion

The methods explored within this thesis offer insight into dynamic hydraulic and physical properties of the pine bark soilless growing media. The porosity distributions outlined by the infiltrometer data were used to characterize the hydraulically active porosity of pine bark, peat + pine, and coir + pine mixtures. The hanging water column experiment defined the water retention characteristics of the three pine bark mixes as well as the screened particle sizes of unamended pine bark. Infiltrometer data outlined the differences in hydraulic conductivity and water repellency between all substrates. Scanning electron microscopy (SEM) methods provided images that let us observe the minute details of particle shapes and surfaces between the substrate mixes and sizes. Gas diffusion methodology delivered the differences between the water content influenced small particle sizes versus the stable rates of the larger particle sizes.

All these experiments together provided details on substrates of different particle sizes and mixes in order to gain a better understanding to inform substrate engineering projects. Coir mixes and the smallest size fractions of pine bark had the best combination of water retention and hydraulic conductivity. The smaller sizes also showed more water repellency, but it was quickly overcome, dissipating within the first 3-15 minutes of infiltration. The largest size fractions had the most favorable gas diffusion rates in combination with the least amounts of water retention. Future work may specifically consider how these different mixes can be implemented together to optimize plant water uptake and growth. The employment of stratified systems with properly chosen amendments (e.g., coir) and particle sizes (e.g., <2 mm particles placed over 2-6 mm
particles) is one way this work can be applied to maximize water retention, gas diffusion, and plant production of these pine bark soilless substrates.
References


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