

## ABSTRACT

YAP JR., TED CHRISTOPHER. Influence of Processing and Preconditioning on Hydration and Wettability of Traditional and Alternative Horticultural Substrates. (Under the direction of Brian E. Jackson).

The ability of a substrate component (organic or inorganic) to capture and retain water (hydration and wettability) is integral for its use as a greenhouse substrate component. Many factors play a role in a substrate's wettability including the processing of the material as well as its preconditioning, previous exposure to moisture, exposure to dry conditions etc. One goal of this research was to determine the effect of preconditioning a substrate by drying or rewetting to different testing moisture content might have on the ultimate wettability of that material. Pine bark, coconut coir, and peat moss were tested at 33%, 50% and 66% testing moisture by weight. These components received different methods of preconditioning in order to achieve these testing moistures, either by drying down from a higher moisture content or by exposing the materials to one cycle of drying and rewetting from 25% moisture content. The preconditioning of a substrate was shown to have an influence on the materials resistance to hydration regardless of testing moisture between all testing materials.

Further objectives of this research were to 1) quantify the differences in wettability between two pine bark materials processed through different methods and one pine wood material and 2) determine where the effects of wettability lie within the particle size distribution of the materials i.e. which particle size(s) most influence wettability. Two differently processed pine bark materials and processed pine wood were tested at 50% and 25% initial testing moisture by weight. X-Large, large, medium and fine particle fractions of

these materials were also tested at 50% and 25% testing moisture in order to determine their wettability. Data from these experiments provide evidence of significant variability between the overall wettability of the bark and wood fractions. Though it is generally thought fines contribute the most to water holding, data from this study provide evidence that medium particle size fractions may contribute significantly to the wettability of a material. Fine particles of wood exhibited more hydrophobicity than did fines from both bark materials.

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Influence of Processing and Preconditioning on Hydration and Wettability of Traditional and Alternative Horticultural Substrates.

by  
Ted Christopher Yap Jr.

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APPROVED BY:

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Brian E. Jackson  
Committee Chair

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William C. Fonteno

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Mike D. Boyette

## **DEDICATION**

I would like to dedicate this work to my mother, Marie Yap, for showing me that beyond circumstance and through perseverance you can make something better despite what was given to you. Thank you for always encouraging and allowing me to pursue my dreams and passions.

## **BIOGRAPHY**

Ted Yap was raised in Old Fort, North Carolina. He graduated with honors from McDowell High School in 2008, graduated cum laude from North Carolina State University in 2013 with a Bachelor of Science and Bachelor of Arts in horticulture and psychology respectively, and graduated from North Carolina State University with a masters from the Department of Horticultural Science in May 2015.

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## Introduction

### Wood Substrates & Substrate Components in Horticulture

Plants grown in containers for horticultural crop production are grown in soilless potting media known as horticultural substrates. Substrates are considered soilless because field soil is not used to grow container plants, and the substrates are composed of a mixture of several organic and inorganic materials (Schmilewski, 2008). Such materials may include peat, coconut coir, compost, perlite, vermiculite or other similar components. Traditionally pine bark has been the most abundantly utilized horticultural substrate component in the nursery crop production. Bark from different pine species is utilized as a substrate component depending on location; Jack pine (*Pinus banksiana* Lamb.) and red pine (*Pinus resinosa* Aiton.) are used in various regions expanding through the Northern United States and Canada. In the southeastern United States loblolly (*Pinus taeda* L.), slash pine (*Pinus ellottii* Engelm.) and longleaf pine (*Pinus palustris* Mill.) are the predominant pine species harvested for pine bark substrates (Bilderback et al., 2013).

Often bark intended for horticultural use is a secondary product from lumber production and pulp and paper manufacturers. Logs intended for use in these industries are debarked in a variety of ways and the bark is then sold to horticultural bark suppliers. Debarking can be accomplished in a number of different ways. Drum debarkers are rotating drums through which several logs enter a horizontal chamber and are subsequently debarked through abrasion against each other and the interior of the drum (Koch 1964). Ring debarkers, another debarking system in which various types of scrapping and curved tools are

fixed on a rotating ring are also commonly used to debark logs. These tools apply radial and tangential pressure while the log passes through the rotating ring effectively removing bark. Other methods of debarking logs include rosser head debarkers and pole shavers which feed logs longitudinally past a fixed device shaving the bark off the log while simultaneously rotating the log (Koch 1964). Variation in the debarking tool fixed on these debarkers, feed rate, season of harvest, and size of the log being debarked results in a large amount of variation in the quality and particle size of bark produced through these different methods.

No industry standards are set for how bark is treated and handled once received from being initially debarked. Bark suppliers handle and treat bark entering their facilities in a number of ways with a variety of different equipment, further causing variation not only between bark suppliers but also at times, within the same source. Bark is generally processed in some way when first received by a bark supplier in order to reduce particle size. Depending on the supplier materials may be screened to a specific size and then aged outside. Aging is done by bark being piled up at varying heights and turned periodically. Aging bark between 6 months to 1 year allows for particle size to be broken down further and has become common practice in the industry rather than using fresh, non-aged material. Composting of pine bark is conducted under more specifically controlled conditions than aging. The process of composting bark consists of controlling the amount of moisture, aeration and the amount of nitrogen throughout the stacked material (Van Schoor et al., 1990).

Bark supplies are highly variable in stability and particle size depending on processing techniques and how long it is aged. Using fresh pine bark versus aged pine bark

is a topic of frequent discussions among nursery professionals, as aging bark may reduce nitrogen tie-up and growth suppression of plants (Nelson, 2012).

Pine bark as a component generally comprises 100% of the total volume of container substrates in the southeast; additionally many growers add sand to the total volume of the container (Lu et al., 2006). Northern areas in the United States use less pine bark but substrates are still generally found to be composed of 60% to 80% pine bark by volume (Altland and Krause, 2012). Pine barks common utilization in nursery substrates due to its physical and chemical properties that promote plant growth, including bulk density, porosity, wettability and pH. Commonly, the remaining volume of substrate is primarily composed of varying percentages of sand and sphagnum peat moss (Bilderback et al., 2013).

Since 2005 interest has peaked in the use of wood-based substrate components as a replacement or extender of pine bark-based mixes (Jackson and Fonteno 2013; Wright and Browder 2005). The major catalysts behind this interest in alternatives stems from recent increased costs and lower supplies due to proposed government subsidies for biofuel (Jackson and Fonteno, 2013), and the fact that companies producing pine bark see an advantage in selling their bark for fuel because it can command a higher price than is currently received from substrate suppliers and growers (Nelson, 2012). Loblolly pine is also widely planted and used by the pulp and paper wood industry, and being utilized as a fuel source, effectively decreasing the availability of bark and increasing costs. Additionally, increased cost from shipping bark from sources outside of its locally harvested location makes alternatives to pine bark more attractive. There is also increased concern with variability in pine bark consistency, water-holding capacity, and hydrophobicity from

supplier to supplier (Jackson and Fonteno, 2013). The processing and handling of pine bark has changed in recent years, which has led to changes in pine bark product quality and performance in substrates (Jackson and Fonteno, 2013). Work done with wood components and their effect on substrate physical and chemical properties, as well as plant growth, has led to the belief that whole tree logs processed into a container substrate may be a suitable and economical alternative. Trees are renewable, reasonably priced, and widespread geographically, as well as small chipped wood particles are often byproducts of the forestry industry (Wright and Browder, 2005).

Laiche and Nash (1986) studied wood components and suggested that pine wood chips and their use as an amendment to pine bark could be improved for plant production if engineered to smaller particle sizes, subsequently creating adequate physical parameters. This material was created by passing pine wood and bark material through a soil shredder with a 12.7 mm screen. Since that work was completed, different methods for producing wood based substrates and their evaluation as an efficient media component have been explored. Several researchers have shown that the utilization of wood as a substrate component is a viable option for growing horticultural crops (Fain 2008; Boyer 2008; Jackson 2008 et al.,; Jackson et al., 2009; Judd et al., 2014). Though numerous tree species have been evaluated loblolly pine has been shown to have the better growth response compared to white pine (*Pinus strobus*) and Virginia pine (*Pinus virginiana*) and is widely available in the southeastern United States (Rau et al., 2006).

Wright and Browder (2005) used chipped pine logs and compared 100% pine bark (PB), 100% pine chips (PC) and 75:25% PC to PB. The pine wood was processed by

chipping logs and hammer-milling the chips to a certain particle size, usually the majority of the particles are in the 2-4 mm size range (Wright and Browder, 2005). Results from this study indicated similar dry weights for Japanese holly grown in all three substrates; however dry weights for azalea grown in 100% PB were higher than both containing chips. Air space percentages for pine chips were higher than pine bark substrates but container capacity and available water was not found to be different for the three substrates. The pH values for the pine chips used in this study were found to be acceptable for plant production. This study also suggested that nutrition and cultural practices may need to be adjusted for substrates containing pine chips.

Saunders et al. (2006) suggested that 100% pine chip substrate could be suitable for plant growth in containers if particle size is adjusted to provide adequate physical properties to support plant nutrient and water requirements. Additionally the physical properties of fine ground pine chips 1.59mm and 2.38 mm in size were within the recommended ranges for easily managed substrates as defined by Bilderback et al. (2005). These ranges include: total porosity (50% to 85%), air space (10% to 30%), and container capacity (45% to 65%) (Bilderback et al., 2014).

Fain (2006) described the use of *WholeTree* (WT) substrates for the production of greenhouse crops. *WholeTree* is another wood-based substrate, it is made from whole portions of pine trees, wood, bark, needles, and cones. As a whole it consists of approximately 80% wood, 15% bark, and 5% needles (Fain et al, 2008).

In 2008, Boyer evaluated the use of clean chip residual (CCR) another wood-based substrate produced from material left over from thinning 10-15 year old pine stands. Clean

chip residual is composed of roughly 50% wood, 10% needles and 40% bark. After comparing this material to standard pine bark mixes, 100% CCR and CCR blended with peat was found to be a viable alternative substrate, producing similar plant growth for several plant species (Boyer et al., 2009). Boyer et al. (2008) initially processed CCR through a horizontal grinder with 101.6 mm screen and then through a swinging hammermill with 19.05 mm screen or a 322.58 mm screen and compared the materials to standard pine bark mixes. These substrates were found to be a viable alternative to PB in greenhouse production of ageratum, salvia and impatiens grown in containers. The positive impacts on plant growth, as well as the broad range of availability of CCR from thinning operations, support this product as a feasible and attractive option for plant production (Boyer et al., 2012). Murphy et al. (2010) compared CCR and *WholeTree* substrates passed through a 9.5 mm screen. Particle size distribution was determined for all mixes used in this study; and it was determined that the number of fine particles has a significant influence on the water holding capacity of the substrate. The data also indicates that growers could amend standard PB mixes with up to 75% CCR or WT with little difference in plant growth and overall root health compared to plants solely grown in pine bark.

Jackson et al., (2010) evaluated plant growth in pine tree substrates (PTS) made from delimbed loblolly pine trees processed through varying hammer mill screen sizes, 4.76, 6.35, 9.54, and 15.8 mm as well as one PTS hammered without any screen. Pine tree substrate processed at each of these screen sizes was also amended with 25% peat, 10% sand, processed with 25% aged pine bark by volume or left unamended. The results from this study show that PTS produced at a smaller screen size (4.76 mm) had higher plant growth and

container capacity compared to those produced with larger screens, additional increases in container capacity and growth were found when PTS was amended with peat moss or hammered with PB. Jackson et al. (2010) concluded that amending coarsely ground materials with finely milled PTS or other materials could result in plant growth similar to pine bark mixes. One advantage in the production of PTS is the ability to manipulate the physical properties of the materials through the milling process (Jackson et al., 2010).

Additionally, wood fiber substrates based out of Europe have been found to be viable horticultural substrate products. Gruda and Schnitzler (2004a; 2004b) worked with spruce (*Picea* sp.) wood fiber substrates (WFS) supplied by INTERTORESA (Switzerland). Gruda and Schnitzler (2004a) examined the physical properties of both a coarser and finer spruce WFS. Both of these wood fiber substrates resembled peat substrates with the amount of total pore space, the finer WFS had a high air volume compared to peat, and mixing both WFS and peat substantially improved the air volume (Gruda and Schnitzler, 2004a). Sieving for particle size distribution of these materials was held within the following ranges: > 4, between 2 and 4, 1 and 2 and < 1mm and revealed the fractions of 14.0, 40.0, 23.2 and 22.8% for the coarser material and 3.3, 15.0, 25.0 and 56.7% of total weight for the finest wood fiber (Gruda and Schnitzler, 2004a). Both wood fiber substrates ranging from the coarsest particles sizes to finely shredded have been shown to be suitable for replacing peat in the production of some crops (Gruda and Schnitzler 1996; 2004a; 2004b).

The use of chipped pine logs and trees have been widely researched in recent years and have led to the discovery that pine tree substrates are an acceptable and sustainable alternative greenhouse and nursery substrate, as well as a suitable substrate component with

peat moss and pine bark. Research suggests that depending on how the material is processed and handled pine wood substrates may be a feasible option for use in replacing or amending pine bark even though amendment with pine wood results in changes of the physical properties of the substrates. These changes in substrate physical properties may lead to alterations in irrigation and/or fertilization practices; however these physicals properties of pine wood substrates are still acceptable for plant growth (Altland and Krause, 2012).

There are many known variables in the process of producing pine wood substrates, as the process is dependent on the method, equipment and materials. These variables could cause discrepancies in the reliability of the method and how the processed wood actually affects physical properties and plant growth. These factors include blade wear, screen size, moisture content, tree species, tree part, chipper and hammer mill type, and the time of year when harvesting wood material. The potential variability these factors may cause have significant effects on the energy required to produce, as well as the quality and reproducibility of wood substrates.

### **Pine Bark**

There has been found to be high variability in the physical properties of pine bark between and even within sources, coupled with the considerable variation observed in the size and shape of processed pine bark (Airhart et al., 1978; Jackson., 2014) growers can experience fluctuations in the performance of their substrates. Reasons for this variability include shifts in consumer demand for pine bark, inconsistencies in the equipment and

methods used in its processing and handling, season in which trees are harvested and bark is removed, and the utilization of fresh versus aged pine bark.

Aged bark has been shown to have a greater amount of available water and higher container capacity than fresh pine bark (Bilderback et al., 2005; Harrelson et al., 2004). This of course means that irrigation management would be expected to differ between aged and fresh materials, with fresh bark requiring more frequent irrigations of smaller amounts of water. Intuitively one could also expect that the extent (how long) and process (how often it was turned) of aging would have an influence on the particle size and resulting water holding characteristics of the material as any alteration in particle size distribution can lead to significant changes in these properties (Richards et al. 1986). Inconsistency in pine bark has been a catalyst for heightened interest in alternative substrates (Jackson and Fonteno 2013).

Plant available water in mineral soils is localized on particles or within pore spaces located between particles. The characteristics of these pores are important as they determine how water moves throughout the substrate (Brown and Pokorny, 1975). Horticultural substrates are much the same as mineral soils, in that plant available water can be found on or between particles, it has been shown though that plant available water can also be found within internal bark pore spaces. Pokorny and Wetzstein (1984) showed that plant roots are able to enter into bark particles, effectively increasing the amount of water available for plant use. Bark internal pore spaces make up a considerable amount of the total volume of a bark particle, in some cases up to 43% of a particle (Pokorny 1987). This variable of internal pore spaces creates a new dynamic for the study of water relations with horticultural and organic substrates compared to plant-water relations in mineral soils. Further, the limited root zone

and substrate volume of plants grown in container production results in a greater need for attaining adequate substrate physical properties, compared to field grown plants in order to aide in optimal water availability (Raviv et al., 2002). Knowledge of a materials surface and internal water holding capabilities could lead to the formulation of horticultural substrates even more favorable for plant production.

### **Substrate Physical Properties**

Substrate physical properties such as water holding capacity, particle size distribution, air space, total porosity, and bulk density all have a significant influence on the growth of horticultural crops. They are known to affect all resources in a container including water and air space as well as the availability of nutrients. This is especially important because the ability of a material to retain water and the amount of air space influences the necessary irrigation rate and frequency during plant production (Nash and Pokorny 1992). Therefore inappropriate substrate physical properties may have characteristics deleterious to plant growth, such as those that hold too much water and limit root development and overall plant growth (Bilderback 2005). The physical properties of a substrate have a direct relationship with the particle size distribution. The engineering of specific particle size distributions allows growers the ability to influence the physical properties of horticultural substrates (Richards et al. 1986). This allows for the ability to alter such properties such as bulk density. Since total porosity, air space and the amount of water held in a substrate decrease as bulk density increases (Fernandes 2004) one could see the appeal in the ability to alter bulk density. Handreck (1983) suggested that increasing the number of small pore spaces and

limiting the amount of freely draining macropores could improve water availability to plants. Additionally, The use of equipment such as a hammer mill allows for easy manipulation of physical properties of wood substrates, however there is a need to develop systematic methods for their manipulation.

There are many different techniques used in measuring particle size distribution. The technique utilized in the analysis of particle size is of particular importance. Hartmann (2001) illustrated that available measuring devices are greatly variable. This means that particle size distribution data often cannot be compared, as different screening operations for measuring size distribution will under and overestimate the distribution of particles depending on method used.

One method for determining particle size distribution is the use of horizontal rotating screens. These rotating cylindrical screens are arranged starting with the smallest aperture or opening to the largest screen size being at the end. Another method involves image analysis system that utilizes digital cameras and computer application to measure particles (Hartmann et al., 2006). The most commonly used process in horticulture is through the use of horizontal screens arranged vertically creating a tower. They are arranged beginning with the largest screen size on top to the finest size at the bottom. Commonly, oven dried material is used in the particle size analysis in order to prevent particles from sticking to the screens during the sieving process. In order to determine particle size distribution a known weight of oven dried material is placed on the top screen. Next the whole set of screens is placed into a mechanical shaking device which loosens the particles and allows the small particles to fall through the screens of decreasing size. After the shaking of the material for a set amount of

time the amount of material on top of the individual screens is weighed in order to determine particle size distribution.

### **Wettability**

The wettability of a material is related to its inherent hydrophobic or hydrophilic characteristics. These characteristics influence the ability of a liquid to spread over a materials surface (Letey et al., 1962). Factors that contribute to wettability include a given substrates inherent surface characteristics, how the material is processed and management of the substrate during production. Naturally, adequate and uniform wettability of a horticultural substrate is optimal for quality plant production. However many horticultural substrate materials, such as pine bark and peat, experience hydrophobicity at low moisture levels (Beardsell and Nichols., 1982; Fonteno et al., 2013; Michel et al., 2001) which in turn has deleterious effects on irrigation efficiency as well as for quality crop production. Further advantages of a substrate material being able to capture water include maintaining plant quality in post-production retail environments.

Similarly to mineral soils, organic substrates exhibit hysteretic behavior (da Silva et al., 1993; Heinen and Raats, 1993). Consequently, irrigation and drying cycles of substrate materials influence the flow of water through a substrate as well as the materials ability to capture and retain water. Hysteretic behavior in peat has been shown to be more pronounced than in pine bark. However this phenomenon is not observed when moisture conditions are near saturation (Michel et al., 2008; Naasz et al., 2005). The relatively smaller pore sizes of peat compared to bark may be one explanation for the more pronounced observance of

hysteresis. The smallest pores in a peat mix may retain moisture while drying, only allowing macropores to become hydrophobic and consequently more difficult to rehydrate.

Hydrophobicity of a material can cause preferential flow and thus uneven water distribution further hindering wettability of the substrate.

Another factor to be considered when studying hysteresis is the differing structure of substrate materials. For example, the fibrous and fine particle size of peat compared to the coarse and platy characteristics of pine bark contribute to the inherent differences in the hydrophysical properties of these materials (Michel et al., 2008). Additionally, how substrate components are processed can have a large influence on how they perform. Some research suggests that the variation in size and structure of milled pine bark particles may contribute to water holding (Airhart et al., 1978).

Letey et al. (1962) described quantifying the hydrophobic properties of materials through the measurement of contact angles. This method is one of the most commonly used techniques for measuring wettability (Wang 2000). The angle formed between the surface of a given substrate and water provides context for the hydrophobic nature of that substrate. For example, the larger the angle the greater amount of hydrophobicity expressed. Contact angle hysteresis can occur due to the interaction between the liquid and the surface of the materials it rests upon. The angle formed between the liquid and the surface depends on the surface characteristics of the material, smooth, rough etc. and its hydrophobic nature (Hillel 1998). Contact angle hysteresis also occurs due to the direction of the wetting angle, causing greater suction in desorption than in sorption (Hillel 1998). Consequently an understanding of the wettability of a substrate and the factors affecting the movement of water throughout a

material is needed in order to produce substrates with adequate physical properties for quality plant production.

Another method used to measure wettability is known as the water drop penetration time test (WDPT). This method measures the amount of time it takes a drop of water to completely infiltrate the surface of a substrate material (Dekker and Ritsema, 2000; Letey, 1969). The capillary rise method described by Michel et al. (2001) has been found to fit well alongside the WDPT as a method for quantifying the wettability of materials. Recently, Fonteno et al. (2013) described a method known as the hydration efficiency test in order to determine a substrate's wettability. This technique, also utilized and further described by Fields et al. (2014), measures the amount of effluent after known quantities of water are passed through a substrate, this allows for the determination of the quantity of water remaining in the substrate to be determined.

### **Material Comminution**

Wood and bark comminution is the process of reducing large particles into smaller particles. The process of comminuting a material is energy intensive (Cadoche and Lopez 1989) and can be achieved through several different mechanisms such as chipping, shredding and hammer milling. Several factors play a part in the reduction of particle size of materials such as the mechanism of choice, species of wood, temperature, feed rate, moisture content, and maintenance of cutting and hammering mechanisms. For the production of wood substrates used in horticultural crop production, logs are first processed in a chipper and secondarily through a hammermill to further reduce particle size.

## **Wood Chip Characterization and Quality**

Wood chips can be produced in many ways, such as with chip mills or sawmills. In chip mills, entire logs are harvested for the production of wood chips. Wood chips may also be found in the field as part of forestry residues, or wood chips can be a secondary product from sawmill production. Though uniformity in a batch of chips is desired, there is no such thing as the perfect chip (Fuller 2004). This means that the particle size distribution, or the range of wood particle sizes after processing may not be completely uniform. Quality chips are generally defined as those with a consistent size and shape distribution. As mentioned above, many factors play a role in the variation in the size distribution and quality observed when processing chips. All wood chips are heterogeneous and vary in species, size distribution, moisture content, bulk density, freshness, bark content and in amount of impurities (Ding 2005). Chip classification can be defined in several ways depending on size from largest to smallest they include; oversized, overthick, accepts, pins and fines (Horn 2007). When put through a screening process oversized chips are those that will not pass through 45 mm holes, overthick by 8 mm, pins are chips which would pass through a 7 mm hole and are characteristic of long toothpick-like chips that are fibrous and fines of course are the smallest and shortest chips. These chips are either considered too big for the pulping process or so small that they are thought to interfere with the degradation of fibers. The term “accepts” is used for chips that are considered optimal for most pulp and paper mills and are sized in between overthick chips and pins.

The type of chipper used, the amount of blade wear, wood temperature, workpiece length, knife tip speed and other factors contribute to the amount of fines, accepts, oversized

chips and chip quality (Horn 2007; Kofman 2006). Wood temperatures below freezing cause wood to be more brittle and therefore the amount of fines significantly increases during chipping (Hartler 1996). The proportion of small chips has been shown to decrease when increasing feed per tooth, increasing cutting angle, sharpness angle and when cutting speed increases. Chipping logs including bark and foliage will generally lead to greater variation in particle size distribution (Asikainen and Pulkkinen 1998; Nati 2010). Chips intended for paper and pulp manufacturing the presence of bark and foliage is undesirable and would not be accepted within the mill, as they would disrupt the pulp making process.

Chipper maintenance is integral in producing and optimizing chip size distribution. The production of pins and fines increases proportionally with increasing knife wear. Regular inspection and replacement of machine parts is needed in order to achieve this. The inspections and maintenance of machines is usually performed during down time within the facility or conducted when chip quality is visually determined to be lessening. This of course requires regular examination of the chips as they are being processed. Knife wear is a function of the volume of wood being processed, wood species, the moisture content of the wood, and the amount of contaminants, dust, metal, ash, etc. that enter into the chipper (Fuller 2004).

### **Chipper Types**

The basic mechanism for most chipper types consists of a sharp knife passing through a piece of wood across the grain. This involves an initial cut that is then followed by a shearing action as the chips “pop” off from the in feed material (Fuller 2004). Disc and drum

type chippers are the most commonly used machines. The cutterheads within the chippers can either operate in the climb-cutting or conventional cutting direction. Disc chippers are the most common type and are recognized as producing higher quality chips than most other chippers. Disc chippers are also found to produce a more homogenous chip than drum type.

Within a basic disc chipper several straight knives are attached radially onto a disc that spins on a vertical plane. Slots are made around the disc so that chips can move past the back of the disc once they are cut, the knives are fixed at each of these slots. Often there are fanlike blades that catch the chips as they fall out past the disc and blow them out of the chipper hood this is referred to as overhead or blown discharge. Without these blades, conveyor systems are generally put into place and the wood chips are allowed to fall due to gravity below or to the side of the chipper, this is termed bottom discharge. It is important to note that the types of materials being chipped, forest residues, short logs, etc. may cause discharge complications depending on moisture content (Wadkins 2013).

Chip thickness when using a disc chipper is positively correlated with chip length. Chip length is controlled by the distance between knife tip and the disc wear plate coupled with the spout angle of the chipper (Hellström 2010). If the wood being fed into the chipper is fed at a steeper incline for gravity fed chippers then thinner chips will occur. Similarly thinner chips can occur by altering the knife sharpness angle. The formation of small chips will vary based on seasonal changes of logs due to temperature and moisture content (Hellström 2010). It has been observed that chip thickness increases with increasing moisture content (Buchanan and Duchnicki 1963). The anisotropic nature of wood also has

an effect on chipping. Cutting in the radial direction of growth rings has been shown to give a more uniform chip thickness than cutting tangentially (Kivimaa and murto 1949).

Productivity and fuel consumption of chippers has been found to be strongly related to piece size, additionally it has been found that tree part has its own additive effect on fuel consumption. The processing of larger tree parts will result in higher productivity and lower fuel consumption (Assirelli 2013).

### **Secondary Comminution: Hammermilling**

After primary wood comminution, the production of pine tree substrate involves hammer milling wood material. Properties of the feedstock processed through the hammer mill such as moisture content of the wood, chip size, and species as well as mill factors such as hammer speed, energy requirements, rate of grinding, and screen size all influence the physical properties of the resulting material (Manlu Yu 2003). Material fed into the chamber of a hammer mill is met with multiple hammers rotating around a spindle located at the center of the chamber. These hammers can be fixed or freely swinging. The impact of the hammers on wood, the wood coming into contact with the walls of the chamber and the contact that the wood material has with itself contributes to size reduction until the wood is small enough to pass through a fixed screen located on the bottom of the chamber. These screens have specified dimensions and can be changed depending on the desired size of material after processing.

The low maintenance required for hammermills and their versatility in comminuting particles are some of the advantages versus other methods such as crushing and rollermilling.

When hammers wear down they can be rotated and inverted to be used in different positions, contributing to the low maintenance requirement.

### **Moisture Content & Energy During Milling**

The moisture content of wood is the weight of water in wood expressed as a fraction. In softwood species the moisture content of sapwood is generally greater than in heartwood. The fiber saturation point of wood is the moisture content at which only the cell walls are completely saturated but no water exists in the cell lumen. It is also considered the moisture content in which the physical and mechanical properties of wood begin to change as a function of moisture content. The average fiber saturation point is around 30% however this can vary greatly by species (Simpsons 1999). Moisture content of a wood material during hammermilling will have a significant influence on the comminution process (Miao et al., 2011; Mani et al., 2004). The amount of moisture present in a material is directly correlated with the energy consumption required to achieve size reduction of materials. As they are found to be correlated (Naimi 2012) understanding of the moisture content of in feed material could allow for predictions of energy required for grinding. Higher moisture content has been shown to lead to higher specific energy consumption during processing (Mani 2004). Conversely, hammermills are able to take advantage of the shattering of wood materials that have very low moisture contents (Dooly 2013).

It is also important to be aware of the moisture content of infeed material in order to prevent bridging over the mill screen. Bridging is the formation of wood particles over screen openings, which could result in material being inhibited from exiting the grinding

chamber, increasing the amount of time particles are able to come into contact with one another, grinding hammers, and the wall chamber (Mattsson 2003). Bridging has been shown to be significantly influenced by proportion of long particles, moisture content and may be dependent on particle shape (Mattsson 2003). Clogging of screen due to moisture content (Miao et al., 2011).

The energy required during milling increases with decreasing final particle size. Further the relationship between energy consumption and degree of size reduction is not linear, varying by material and by mill type. For example, the energy required for knife mills is generally lower than for hammer mills (Cadoche and Lopez 1989). Miao (2011) found a larger percentage of fine particles when using a mill fitted with knives than with hammers when grinding *Miscanthus* (*Miscanthus giganteus* Greef et. Deu.).

Increasing hammer speed during grinding has been shown to result in a fine material size. This is a function of both the increase in specific energy of impact as well as the increased frequency in hammers making contact with the material (Austin 2004). The increase in hammer speed is positively correlated with an increase in total specific energy (Bitra 2009). Particle size found to be inversely proportional to bulk densities of biomass particles (Miao et al., 2011). The amount of fines in a material is dependent on screen size and the rate of movement through the grinder (Yu et al., 2006).

Energy output needed for the grinding of materials is a function of the energy required for crushing materials and their mean residence time, or average amount of time spent in the grinding chamber. The mean residence time of a particular material is dependent on the natural breakage characteristics of the material (Endoh 1992, 1993). Grinding with a

larger hammer mill screen size will lower the amount of energy needed for comminution (Mani 2004). Naimi (2012) found softwoods to have lower specific energy consumption of grinding but included particles larger in comparison to hardwoods when grinding in a knife mill. The mechanical properties of wood have a direct influence on how it will react during the comminution process. The properties of wood vary greatly not only between species but also within the same tree, as it has very specific structural stages i.e. earlywood latewood, and transition wood (Hellström 2010).

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## Chapter 1

### Effects of Preconditioning on the Wettability of Traditional and Alternative Horticultural Substrate Components

**Additional Index Words:** hysteresis, wettability, pine bark, peat, coconut coir

#### **Abstract**

The ability of a substrate component (organic or inorganic) to capture and retain water (hydration and wettability) is important for it to be used to grow horticultural crops in containers. Many factors play a role in a material's wettability including the processing of the material as well as its preconditioning, previous exposure to moisture, exposure to dry conditions etc. The goal of this experiment was to determine the effect of preconditioning a substrate by drying or rewetting to different testing moisture content (TM) might have on the ultimate wettability of that material. Pine bark, coconut coir, and peat components were tested at 33%, 50% and 66% TM by weight. These components received different levels of preconditioning in order to achieve these TMs, either by drying down from a higher moisture content or by exposing the materials to one cycle of drying and rewetting from 25% moisture content. This experiment provides evidence that the preconditioning of a material influences the materials resistance to wettability regardless of TM between all testing materials.

## **Introduction**

Substrate physical properties such as water holding capacity, particle size distribution, air space, total porosity, and bulk density all have a significant influence on the growth of horticultural crops (Bilderback et al., 2005). This is especially important because the ability of a substrate to retain water and the amount of air space influences the necessary irrigation rate and frequency during plant production (Nash and Pokorny 1992).

Adequate and uniform wettability of a horticultural substrate is optimal for quality plant production. However many horticultural substrate materials, such as pine bark and peat, experience hydrophobicity at low moisture levels (Beardsell and Nichols., 1982; Fonteno et al., 2011; Michel et al., 2001) which in turn has deleterious effects on irrigation efficiency as well as for quality crop production. Further advantages of a substrate material being able to capture water include maintaining plant quality in post-production retail environments.

Similar to minerals soils, hysteresis has been observed in organic substrates (da Silva et al., 1993; Heinen and Raats, 1993). Consequently, irrigation and drying cycles of substrate materials influence a given materials ability to capture and retain water. Hysteretic behavior in peat has been shown to be more pronounced than in pine bark. However this phenomenon is not observed when moisture conditions are near saturation (Naasz et al., 2005). The utilization of a substrate component, whether for analytical or commercial purposes, determines whether or not materials need to be hydrated or dried before use. For example, analytical techniques such as the NCSU Porometer Method (Fonteno et al., 1995) require different substrates to consist of specific moisture contents in order to be accurately

tested. Pine bark is generally shipped by the truck load and can vary considerably in moisture content. Peat moss is commonly packaged and shipped in compressed bales and needs to be fluffed either mechanically or by hand before being used. Similarly coconut coir is found shipped in compressed brick form and requires the addition of water in order to aide in fluffing the material before use. Since different materials are handled and shipped in a variety of conditions their packaging and moisture content when received may have an influence on their wettability.

Three ways of describing moisture found in a substrate are moisture content, mass wetness and volumetric water content. Moisture content is the percent moisture found in a substrate on a wet mass basis. Moisture content is commonly used to illustrate how much of a total sample contains water. Mass wetness, which is correlated to moisture content, is the determination of water content of a sample on a dry mass basis. Mass wetness values are useful in calculating the amount of water needed for addition in order for various lab techniques. Volumetric water content describes how much of the total substrate volume contains water.

The variability in handling and conditioning of different substrate components at various moisture contents before commercial and analytical utilization may play an important role in the wettability of a given substrate. The first objective of this study was to determine the effect of preconditioning a substrate by drying or rewetting to specific moisture content might have on the ultimate wettability of that material. After observing the wetting behavior of peat, a second objective was established in order to determine the effect coconut coir additions might have on mitigating the wettability of a peat based substrate.

## Materials and Methods

*Experiment 1:* Substrate materials tested were aged pine bark (*Pinus taeda* L.; Pacific Organics, Henderson, NC), professional grade sphagnum peat moss (Berger Peat Moss, Canada), and coconut coir (Densu Coir, Ontario, Canada). White wood content of the aged pine bark was determined by taking three 1000 ml samples of pine bark, separating white wood and bark by hand and measuring the total volume of white wood for each sample. White wood percentages were determined as some studies provide evidence for the decreased presence of white wood in pine bark aged from 6 months to a year contributing to the wettability of pine bark.

To determine particle size distribution, three 100 g samples of each material were dried at 105°C for 48 hours and placed in a Ro-tap Shaker (Model B, W.S. Tyler, Mentor, Ohio) for 5 minutes with 4 sieve sizes of 6.3, 2, 0.71, 0.5 mm and a pan at the bottom to collect all materials that passed through the smallest sieve. This analysis was also conducted as particle size distribution is known to be correlated to the water holding characteristics of horticultural substrates (Bilderback 2005).

Moisture content of all three materials was determined by taking three representative samples of 200 ml of each material, weighing, oven drying for 24 h and reweighing. Knowing the initial wet weight and dry weight of a substrate allows for the ability to calculate MC. Moisture content of the peat out of the bale was 38% by weight. Pine bark was initially at 55% MC and coconut coir was at 15% MC when still in compressed brick form.

A mass wetness of 1 (50% MC) is the most commonly used MW for substrates commercially as well as for wettability analysis. Mass wetness values of 0.5 and 2 were used in order to represent half and double the MW of 1 commonly used for substrates in the trade and in research settings. Each substrate component was subject to either wetting up (WU), 1 drying/rewetting cycle (RW), or drying down (DD) in order to obtain values of 0.5, 1 and 2 mass wetness (MW), equivalent to 33, 50 and 66% moisture content (MC) by weight respectively. Percent moisture content is determined on a wet mass basis. Mass wetness is calculated on a dry mass basis. Substrates subject to WU treatment were wet to 66% MC. The DD treatments were initially wet up and allowed to air dry by spreading 300 ml of each substrate 4 cm deep on a tray until reaching desired MC while RW treatments were allowed to air dry to a much lower MC at 25%, with water subsequently added in order to attain the same MCs.

Peat and bark treatments were hydrated to a MW of 2 and allowed to equilibrate for 24 h within sealed 55-L plastic bags in order to prevent moisture loss. Coir material was hydrated to a MW 7.3 (88% MC) in order to be fully fluffed out of compressed form, placed in a sealed plastic bag and allowed to equilibrate for 24 h. The differences between how the materials were initially wet was due to the inherent differences in how the materials are packaged and shipped as well as the volume of water they are able to hold. Sphagnum peat is more easily fluffed out of compressed bale form than coconut coir, which is a material that commonly requires the addition of water in order to be expanded. Following the equilibration period, 2 subsamples of 300 ml of each substrate were spread 4 cm deep on a tray and allowed to air-dry in order to reach MW of 1 and 0.5 designated as DD treatments. Substrates

were weighed hourly in order to monitor moisture loss. Bark and peat samples initially hydrated to a MW of 2 were designated as wet up treatments (WU) and were tested for wettability immediately after the 24 h equilibration period. After remaining dry down treatments attained their desired MW, substrates were placed back into plastic bags, sealed, allowed to equilibrate for 24 h.

In addition to DD substrate components to MW of 0.5, 1 and 2 the same materials were further dried to 0.3 MW (equivalent to 25% MC) and rehydrated (RW) to these same values. Similar to the treatments previously described, three subsamples of 3 L of each substrate component were spread on trays as described above and dried to MW of 0.3. Once attaining this value the materials were placed in sealed bags and allowed to equilibrate for 24 hrs. Each of the three materials were then rehydrated to initial moisture contents (IM) of 33, 50 and 66% by weight for a total of nine rehydrated materials. The amount of water required to bring each substrate to their respective IM was measured in a graduated cylinder and thoroughly mixed into each substrate by hand in a plastic tub. Immediately after each treatment's respective equilibration period water capture and retention of all materials were determined following the wettability protocol described by Fields et al. (2014). There were a total of 18 treatments in this study (3 components x 3 initial MW x 2 methods for attaining MW). Data were analyzed using general linear model procedures and regression analysis (SAS Institute version 9.3, Cary, NC). Means were separated by least significant differences at  $P \leq 0.05$ .

*Experiment 2:* As a follow up to experiment 1, three peat-coir mixes of 85:15, 70:30 and 55:45 peat:coir (vol:vol) from the same sources were tested using the same DD and RW

methods described above at 50% TM. These materials were tested as a result of observing a significant difference in peat at 50% TM between the DD and RW treatments as well as differences in the hydration efficiency of both peat and coconut coir materials. The addition of varying percentages of coconut coir to a peat based mix was conducted in order to observe if this addition would mitigate the difference of wettability between the two materials.

## **Results**

Testing MCs for these experiments (33%, 50% and 66%) were determined on a by weight basis. The curves representing the data for the wettability of treatments described in this study were determined based on volumetric water content, showing how much of the total substrate volume contains water. Therefore the volumetric water contents on the curves before the first hydration event are equivalent to the initial moisture content of the materials. For example, the initial MC of 50% by weight for coir is approximately 6% by volume for the coir used in this study. For bark, the 50% initial TM by weight are around 15% to 17% by volume. For peat 50% by weight is 8% to 9% by volume.

*Coir.* At 33% TM coir DD reached maximum water content of 70.2% after 4 hydration events, while the RW treatment achieved its maximum hydration after 7 hydration events only reaching 65.5%, approximately 5% difference in water content (Fig. 1A). Coir at 50% TM attained similar values to the treatments at 33% TM, 70.2% and 65.9% for the DD and RW treatments respectively (Fig. 1B). For both 33% and 50% TM coir DD treatments attained maximum hydration sooner than when the materials were wet up. Additionally RW treatments at 33% and 50% TM never reached container capacity. Coir treatments at 66%

TM showed similar trends as the lower TM levels with the DD treatment attaining ~5% more water for the DD treatment, 69.1% compared to 64.2% for the RW material (Table 1).

However at 66% TM neither treatment reached CC (Fig. 1C).

*Bark.* At 33% TM bark material DD and WU attained approximately 5% difference in water content after 10 hydration events, with 35.5% and 31% volumetric water respectively (Table 1). Much like peat the dry down treatment for bark attained its maximum hydration sooner, after 3 events than the hydrated treatment, which took 7 events to reach maximum hydration (Fig. 2A). Bark at 50% TM was able to capture significantly more water at the first hydration event than 33% TM with 36.5% for DD and 33.5% for the WU treatment. Maximum hydration for both materials after the last hydration event was 39.8% and 35.1% for bark DD and bark RW respectively (Table 1). In a similar way to 50% TM the same difference in volumetric water content was observed, between 4-5%, was observed between WU and RW treatments at 66% TM (Table 1). At both 50% and 66% TM the DD treatment captured significantly more water after the initial and last hydration events than the WU treatment (Table 1).

*Peat.* Much like the previous materials, peat 33% TM DD retained 4% more moisture than the RW treatment at the same MC (Table 1). Likewise, peat held 5% more water when initially wet to 66% TM than when dried to 25% MC and rewet back up to 66%. The greatest differences observed between DD and RW treatments for all substrates was seen in peat at 50% TM with the DD treatment retaining 20.4% more water at 54.4% compared to 34% for the WU treatment (Table 1). Peat DD wet up much more easily than peat RW even at the same TM (Table 1).

*Peat:Coir Mixes.* All peat and coir mixes were tested at 50% TM. No significant difference was observed with peat:coir 85:15 between the DD and WU treatments attaining 55.8% and 54.5% moisture respectively (Table 2). These treatments did not reach CC (Fig. 4A). The 70:30 peat:coir mix DD treatment did initially hydrate more quickly than the WU treatment, with 70:30 DD retaining 38.2.% moisture compared to 30.8% for 70:30 WU (Table 2), however after 3 hydration events no significant difference was observed through the rest of the hydration testing (Fig. 4B). At 55:45 there was an even greater difference between the initial hydration, with the DD at 41% and the WU at 29.4% (Table 2). Dry down treatment at 55:45 hydrated much more quickly than WU (Fig. 4C) however there was no significant difference between the two after the last hydration event with 63% and 58.8% for DD and WU treatments respectively (Table 2).

## **Discussion**

The trend observed for most of the bark, peat and coir treatments except for bark at 33% TM was that the DD and treatments initially wet to 66% held more water, typically 4-5% more than the treatments that were allowed to dry to 25% MC and wet back up. The difference seen in bark at 33% TM is likely due to the hydrophobicity of the material, the coarser particle sizes compared to the other materials (Table 1) and the lower amount of water found in these samples relative to the other bark treatments. An even greater difference between these treatments was observed with peat at 50% TM with the DD treatment retaining 20.4% more water than the treatment wet up from 25% MC (Fig. 3B).

It should be noted that although all of the peat and bark materials at 66% TM were wet up from a lower MC and there was no true DD to 66% TM, the RW material was hydrated from a much lower MC of 25%. The implications for all of these materials is that the DD treatments and the bark and peat materials that were tested at 66% TM were never exposed to as dry conditions as those materials wet up to the same MC from 25% MC. The procedure for attaining a particular TM (drying versus rewetting) is one condition for hysteretic phenomena, creating differences in how the materials captured and retained water.

Considering all materials were initially wet to the same level, substrates that were dried to 25% MC likely had greater variation in the ability of the water to spread across the material during rewetting altering the contact angle formed between the surface of the material and the water. When materials air-dried, moisture left the surfaces and pore spaces of the substrates and possibly led to small isolated surfaces that did not retain water as well compared to materials that were initially forced to have water throughout the whole of the substrate and then dried down, which had an easier time capturing higher amounts of moisture consistently between all substrates.

Wettability of the peat:coir mixes was mitigated compared to the homogenous peat and coir mixes. That is the general behavior observed by coir, quickly hydrating and peat gradually hydrating seemed to trend in between the whole non-mixed material as far as how quickly the materials hydrated and their maximum hydration values. As the peat:coir mixes also gradually hydrated but retained a volume in between the peat and coir homogenous materials. At 55:45 behavior of coir dominated the mix. With the initial heterogenous

mixing of peat and coir a large amount of variation occurs initially until the 55:45 treatment in which variation decreased and materials captured water in a more consistent manner.

It is understood that hydrophobicity is related to MC of a material. Hydrophobicity and hysteresis can also be seen interacting with one another. These data show that the exposure of materials to very dry or wet conditions can have effects on the characterization of a substrate during testing. Depending on the procedure being used for attaining specific MC, different values can be attained. Standards for testing of substrates hydrophysical properties between laboratory techniques need to be in place if comparing between studies utilizing the same methods.

Using peat at 50% MC is an approximate value used when potting plants for horticultural use. Data from these experiments provide evidence that the method for attaining this value of moisture, and how dry the material is allowed to get before wetting can lead to differences, up to 20%, in peats hydration efficiency exhibiting hysteretic phenomenon. Even substrates at 66% TM may lose up to 5% water depending on how they are treated. Other possible implications are that the amount of time between irrigations during plant production may reduce the ability of a substrate to wet back up to its potential container capacity.

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Table 1. Volumetric water content of coconut coir, pine bark and peat moss after an initial hydration event and after 10 hydration events.

<i>Coconut coir</i>				
Testing Moisture <sup>z</sup>	Drying/rewetting cycle	Initial event		Last event
33	DD <sup>y</sup>	51.7 b <sup>x</sup>	* <sup>w</sup>	70.2 a <sup>v</sup>
33	RW <sup>u</sup>	51.4 b	*	65.5 bc
50	DD	58.9 ab	*	70.2 a
50	RW	52.7 b	*	65.9 bc
66	DD	64.2 a	*	69.1 ab
66	RW	58.7 ab		64.2 c
<i>Pine bark</i>				
33	DD <sup>t</sup>	26.7 d	*	31.6 d
33	RW	27.8 d	*	35.4 c
50	DD	36.5 b	*	39.8 ab
50	RW	33.5 c		35.1 c
66	WU <sup>s</sup>	40.7 a		41.7 a
66	RW	36.4 b		37.4 bc
<i>Peat</i>				
33	DD <sup>r</sup>	9.3 e	*	13.7 e
33	RW	8.8 e		9.4 f
50	DD	29.5 c	*	54.4 a
50	RW	24.4 d	*	34.0 d
66	WU <sup>q</sup>	46.0 a		48.8 b
66	RW	42.3 b		43.5 c

<sup>z</sup>Material tested at either 33%, 50%, or 66% initial moisture content, respectively.

<sup>y</sup>Substrate tested at respective initial moisture content after being dried down from 88% moisture content.

<sup>x</sup>Means separated within column across all testing moistures and drying/wetting cycles by substrate using Least Significant Difference (LSD), P<0.05. Means followed by the same letter are not significantly different.

Table 1. Continued

<sup>w</sup>Means separation between initial event and last event represented with \* as significantly different ( $P < 0.05$ ) using LSD.

<sup>v</sup>Means separated within column across all testing moistures and drying/wetting cycles by substrate using Least Significant Difference (LSD),  $P < 0.05$ . Means followed by the same letter are not significantly different.

<sup>u</sup>Substrate tested at respective initial moisture content after being rewetted from 25% moisture content.

<sup>t</sup>Substrate tested at respective initial moisture content after being dried down from 66% moisture content.

<sup>s</sup>Substrate tested at respective initial moisture content after being hydrated from 55% moisture content.

<sup>r</sup>Substrate tested at respective initial moisture content after being dried down from 66% moisture content.

<sup>q</sup>Substrate tested at respective initial moisture content after being hydrated from 38% moisture content.

Table 2. Volumetric water content of three peat:coir substrates after an initial hydration event and after 10 hydration events at 50% initial moisture content.

<i>Substrate<sup>z</sup></i>	<i>Drying/rewetting cycle</i>	<i>Initial event</i>	<i>Last event</i>
85:15	DD <sup>y</sup>	32.4 bc <sup>x</sup>	55.8 b
85:15	RW <sup>w</sup>	38.3 ab	54.5 b
70:30	DD	38.2 ab	56.9 b
70:30	RW	30.75 c	56.2 b
55:45	DD	41.0 a	63.0 a
55:45	RW	29.4 c	58.8 ab

<sup>z</sup>Substrate consists of either 85:15,70:30 or 55:45 peat:coir by volume.

<sup>y</sup>Substrate tested at 50% initial moisture content after being dried down from 66% moisture content

<sup>x</sup>Means separated within column across all testing peat:coir ratios and drying/rewetting cycle using Least Significant Difference (LSD), P<0.05. Means followed by the same letter are not significantly different.

<sup>w</sup>Substrate tested at 50% initial moisture content after being rewetted from 25% moisture content.

Table 3. Particle size distribution of three traditional greenhouse substrate components<sup>z</sup>.

	Coir	Pine bark	Peat
X-large <sup>y</sup>	0.1 <sup>x</sup> c <sup>w</sup>	21.2 a	6.4 b
Large <sup>v</sup>	9.8 c	44.5 a	36.7 b
Medium <sup>u</sup>	47.7 a	20.9 c	35.1 b
Fines <sup>t</sup>	43.1 a	11.9 c	22.1 b

<sup>z</sup>Particle size distribution determined by sieving through column of sieves for five minutes in a shaker.

<sup>y</sup>X-Large Particles are larger than 6.3 mm in diameter.

<sup>x</sup>Values are means of percentages of total sample.

<sup>w</sup>Means separation between all materials by LSD,  $P < 0.05$ . Means followed by the same letter the same row are not significantly different.

<sup>v</sup>Large particles are smaller than 6.3 mm and larger than 2 mm in diameter.

<sup>u</sup>Medium particles are smaller than 2 mm and larger than 0.5 mm in diameter.

<sup>t</sup>Fine particles are under 0.5 mm in diameter.

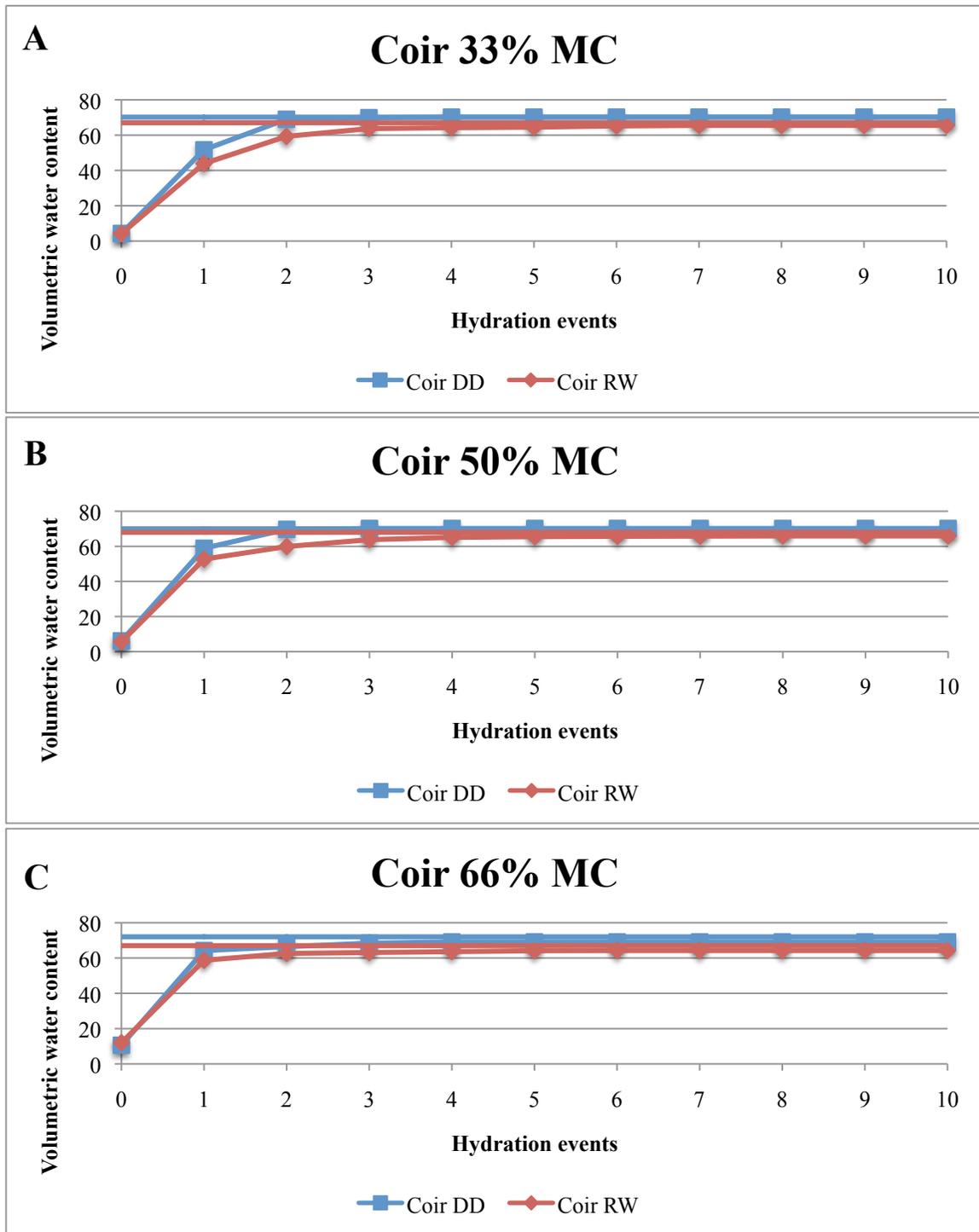


Figure 1. Wettability curves for two methods of preconditioning substrate moisture level (drying down and one drying rewetting cycle) and container capacity lines for A) Coir at 33% MC, B) Coir at 50% MC, and C) Coir at 66% MC.

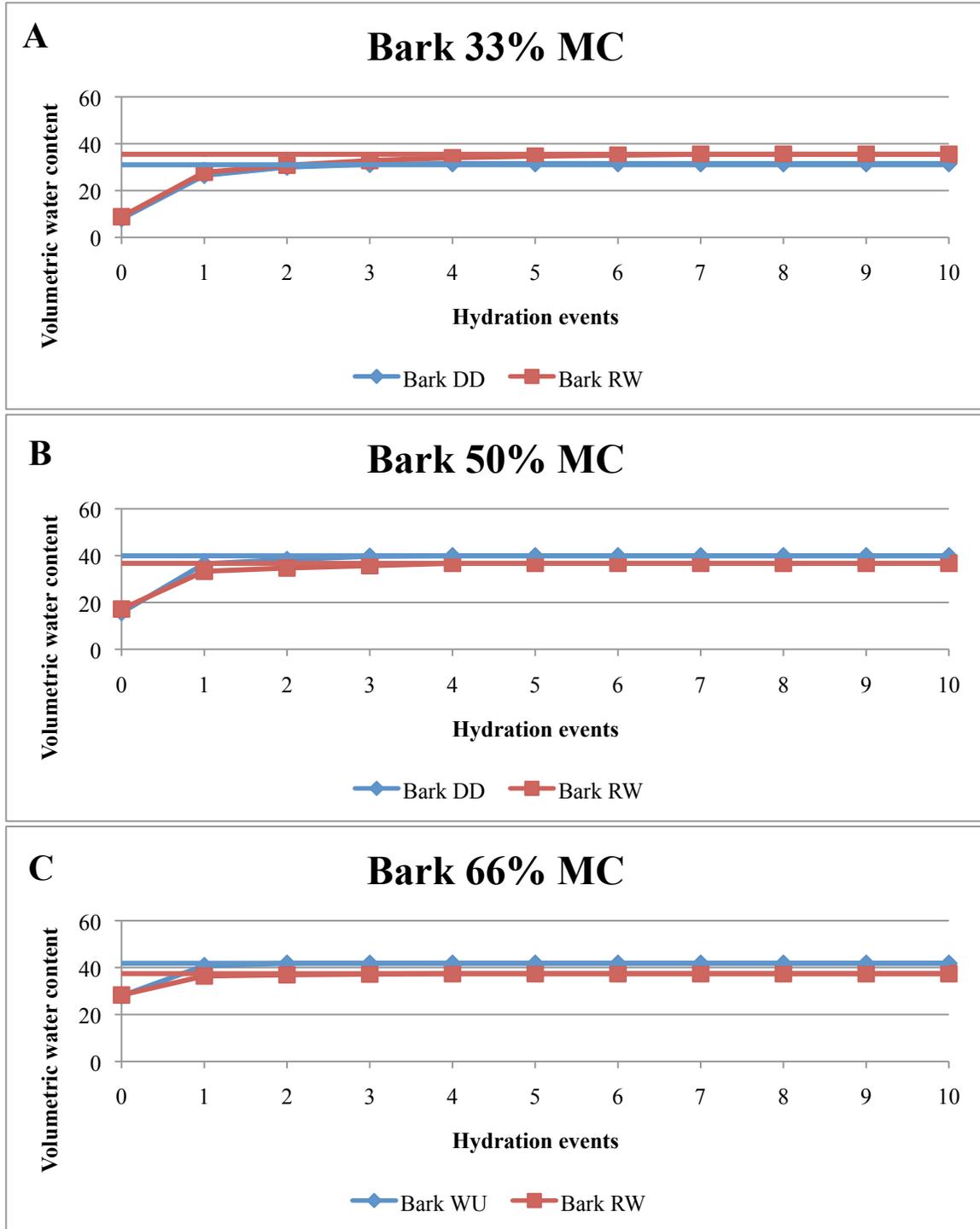


Figure 2. Wettability curves for two methods of preconditioning substrate moisture level (drying down and one drying rewetting cycle) and container capacity lines for A) Bark at 33% MC, B) Bark at 50% MC, and C) Bark at 66% MC.

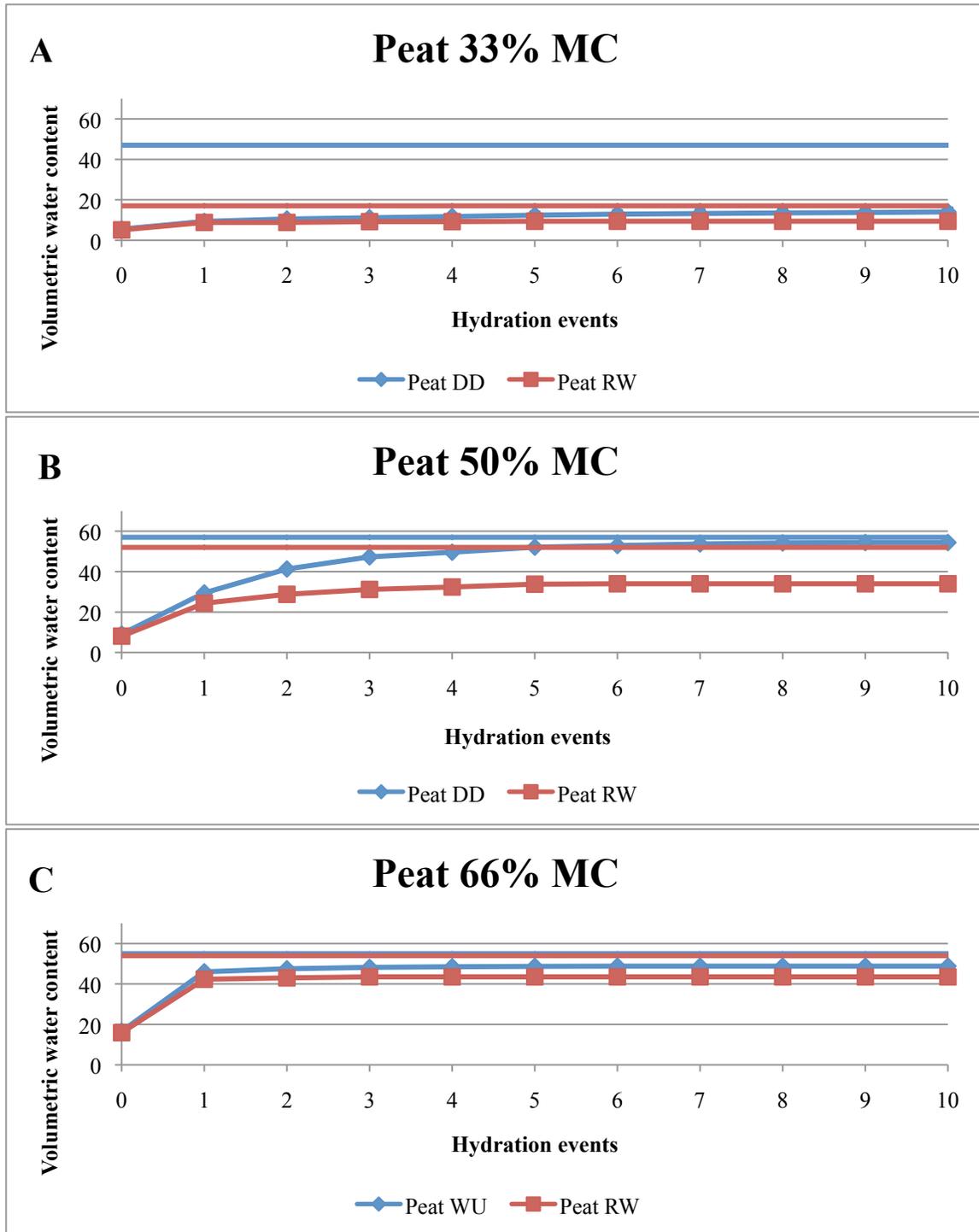


Figure 3. Wettability curves for two methods of preconditioning substrate moisture level (drying down and one drying rewetting cycle) and container capacity lines for A) Peat at 33% MC, B) Peat at 50% MC, and C) Peat at 66% MC.

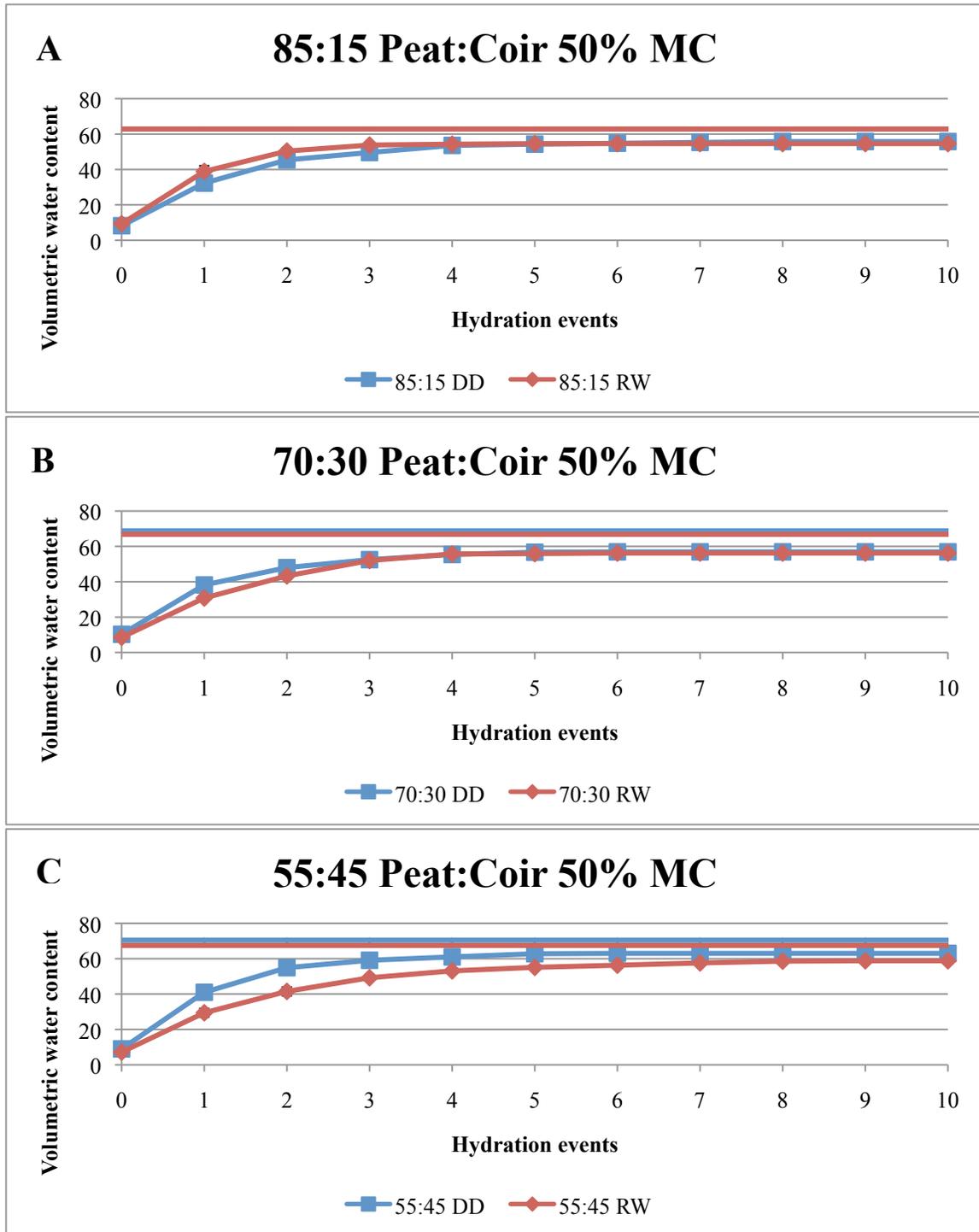


Figure 4. Wettability curves for two methods of preconditioning substrate to 50% moisture content (drying down and one drying rewetting cycle) and container capacity lines for A) 85:15 peat:coir B) 70:30 peat:coir, and C) 55:45 peat:coir

## Chapter 2

### Influence of Processing and Particle Size on the Wettability and Hydration of Pine Bark and Pine Wood Substrate Components

**Additional Index Words:** hammer mill, hydrophobicity

#### **Abstract**

The wettability of pine bark and other materials intended for use as a horticultural substrate is important for sufficient plant growth and production. Inconsistency in pine bark handling and processing leads to variation in barks wettability and water holding characteristics. Due to the variability of pine bark and interest in alternative substrates processed pine wood has been considered as another substrate viable for plant production. This experiment was designed in order to 1) quantify the differences in wettability between two bark materials processed through different methods and one wood material and 2) determine where the effects of wettability lie within the particle size distribution of the materials i.e. which particle sizes influence wettability. Two differently processed pine bark materials and processed pine wood were tested at 50% and 25% initial MC by weight. X-Large, large, medium and fine particle fractions of these materials were also tested at 50% and 25% MC in order to determine their wettability. Data from these experiments provide evidence of significant variability between the overall wettability of the bark and wood fractions. Though it is generally thought fines contribute the most to water holding data from this study provide evidence that medium

particle size fractions may contribute significantly to the wettability of a material. Fine particles of wood exhibited more hydrophobicity than did fines from both bark materials

## **Introduction**

Pine bark is one of the commonly used substrate components in the horticulture industry. However there has been found to be high variability in the physical properties of pine bark between and even within sources, coupled with the considerable variation observed in the size and shape of processed pine bark (Airhart et al., 1978) growers can experience fluctuations in the performance of their substrates. Reasons for this variability include shifts in consumer demand for pine bark, inconsistencies in the equipment and methods used in its processing and handling, season in which trees are harvested and bark is removed, and the utilization of fresh versus aged pine bark. Research suggests that the variation in size and structure of milled pine bark particles may contribute to wettability and the water holding characteristics of these materials (Airhart et al., 1978). Pine bark has been researched for decades, yet little work has been conducted on how processing and handling of pine bark can affect particle size and wettability of the material when intended for use as a substrate component.

Plant available water in mineral soils is localized on particles or within pore spaces located between particles. The characteristics of these pores are important as they determine how water moves throughout the substrate (Brown and Pokorny, 1975). Bark based substrates are much the same as mineral soils, in that plant available water can be found on or between particles, it has been shown though that plant available water can also be found

within internal bark pore spaces. Pokorny and Wetzstein (1984) showed that plant roots are able to enter into bark particles, effectively increasing the amount of water available for plant use. This variable of internal pore spaces creates a new dynamic for the study of water relations with horticultural and organic substrates compared to plant-water relations in mineral soils. Further, the limited root zone and substrate volume of plants grown in container production results in a greater need for attaining adequate substrate physical properties, compared to field grown plants in order to aide in optimal water availability (Raviv et al., 2002). Knowledge of materials surface characteristics, internal water holding capabilities and particle size distribution could lead to the formulation of horticultural substrates even more favorable for plant production.

Manipulating particle sizes and the resultant pore sizes within a substrate could allow the engineering of a substrate with desired plant growing conditions and (Drzal et al., 1997). The processing of pine wood for use in plant production has been more and more common in recent years however due to the lack of research in this area useful particle size distributions of wood-based materials are currently unknown. Sine pine wood particle size is created during milling processes, producers of these materials have the ability to engineer specific particles sizes based on their needs (Nash and Pokorny 1992). Additionally, research needs to be conducted on the individual particle size fractions of organic substrate components and how they contribute to wettability as previous research has shown a considerable amount of internal pore space providing available water to plants. The objectives of this study were to 1) quantify the differences in wettability between two bark materials processed through different methods and one wood material and 2) determine where the effects of wettability lie

within the particle size distribution of the materials i.e. which particle sizes influence wettability.

## **Materials and Methods**

*Experiment 1:* Coarse loblolly pine (*Pinus taeda* L.) wood chips and unprocessed raw pine bark and a standard commercially processed pine bark (CB) were acquired from a local source (Pacific Organics, Henderson, NC) in Southeast NC. The unprocessed pine wood chips and the aged pine bark was processed in a hammer mill (Model 35; Meadows Mills, North Wilkesboro, NC) at the Substrate Processing and Research Center located at the Horticultural Field Laboratory on the campus of North Carolina State University located in Raleigh, NC. These materials were processed (passed through the mill) with no screen inserted in the mill in order to assure a wide variation of particle sizes (known to occur as experienced in personal observations; Jackson et al., 2010). Moisture content of the materials were not adjusted prior to processing but were processed as received at 60% and 45% MC by weight for the pine bark and pine wood respectively. To prevent moisture loss after milling, processed raw pine bark (PRB) and processed pine wood (PW) materials were sealed in plastic 55-gallon drums for further testing.

Particle size distribution was determined using three 100g samples of each material were dried at 105°C for 48 hours and placed in a Ro-tap Shaker (Model B, W.S. Tyler, Mentor, Ohio) for five minutes with six sieve sizes of 6.3, 2, 0.71, 0.5 mm and a pan at the bottom to collect all materials that passed through the smallest sieve. Materials were also sieved as is and grouped into four individual size fractions: Extra-large, > 6.3mm, Large, <

6.3mm > 2mm, Medium, < 2 > 0.5mm and Fine,  $\leq 0.5$ mm. Materials were not oven dried as is typical for PSD analysis, in order to avoid hydrophobicity observed in organic materials and the need to keep the substrates moist for wettability testing. Substrates were sieved at the MC observed after milling and being received, 55%, 57% and 43% for CB, PRB and PW respectively.

The sieved fractions and the non-sieved pine bark and nursery mix, were then hydrated or air dried to a MC of 50% by weight for testing. Additionally, materials were tested at 25% MC. To achieve the lower MC approximately 300 ml of each substrate were spread 2 cm deep on a tray and allowed to air-dry until reaching 50% or 25% MC these materials were weighed periodically in order to monitor moisture loss. A total of 30 treatments were used in this study [3 materials x 5 substrates (four fractions plus the non-sieved material) x 2 MC = 30 treatments]. Water capture and retention of materials were determined by the wettability protocol described by Fields et al. (2014). Data were analyzed using general linear model procedures and regression analysis (SAS Institute version 9.3, Cary, NC). Means were separated by least significant differences at  $P \leq 0.05$ .

*Experiment 2:* In order to determine the effects processing may have on the wettability of bark materials after sieving the particle size fractions of the PRB and CB were recombined to have the same particle size distribution: 15% X-large, 35% large, 25% medium and 25% fine particles. These reengineered pine barks were tested similarly to the materials in experiment 1. All samples were hydrated to 50% moisture (w/w) and allowed to equilibrate for 24 hours. Additionally, materials were tested at 25% MC following the previously explained protocol.

## Results

*Whole materials (unfractionated).* At 50% IM, PRB was able to retain significantly more water (55.9%) than the CB and the PW, which retained 34.4% and 48.2% water respectively (Table 1). Pine wood materials attained the same volumetric water content as PRB after 10 hydration events while CB retained 22% less water than both treatments after the final hydration event (Table 1). At 25% IM no significant difference was observed between any of the materials after the initial hydration event (Table 1). However the PW began to hydrate much more quickly and readily than the other materials (Fig. 1A). After the final hydration event PW held the most water at 55.9%, PRB held 38.3% a significantly higher amount than CB at 31.2 % (Table 1).

*X-Large particles.* At 25% IM, PW particles x-large fraction (>6.3mm) still held the most water throughout each hydration event during wettability testing when compared to bark materials. At the end of testing PW held 31.9% water, which was twice as much as NP Bark 15.9% and significantly more than CB which held 20.6%. Both bark materials reaching maximum hydration quickly while the wood material hydrated in a more gradual trend (1A). At 50%IM retained significantly more water at 33.1% than both the NP and CB materials 22.2% and 24.6% respectively (Table 1). The final hydration event PW held more water than both bark materials, with no difference observed between the two barks. The wood material however did not reach container capacity after the final hydration event compared to the two bark materials which reached container capacity after two hydration events (Fig. 2B).

*Large particles.* Volumetric water content for large particles (6.3 to 2.0mm) of PRB, PW and CB after initial hydration and final hydration events can be seen in table 1. At 50%

IM no difference was observed between the treatments after initial hydration. However after the final hydration event PW held more water with 45.7% than both the PRB 32.5% and the CB 32.9%. Both bark materials reached maximum hydration after 2 hydration events while the wood material reached max hydration after 9 events (Fig. 6). At 25% IM no difference was seen between the treatments after initial hydration (Table 4). All materials at this level seemed to wet gradually (Fig. 7) however PRB held significantly more water than the other two materials after the final hydration event.

*Medium particles.* At 50% IM PRB medium size particles (2.0 to 0.5mm) retained 65.1% water after the initial hydration event, compared to 51.8% and 45.4% for the CB and PW respectively (Table 5). Both bark materials reached maximum hydration after 3 hydration events, PW treatment however gradually reached max hydration over 7 hydration events (Fig. 8) and retained a similar volume of water compared to PRB after the final hydration event with CB retaining the least amount of water (Table 5). At 25% IM all materials behaved in much the same way with no significant difference being observed in initial or final hydration or with the wetting trend observed in Fig. 9. All materials retained between 22-27% water after initial hydration and 48-50% after the final hydration event (Table 5).

*Fine particles.* At 50% IM fine particles ( $\leq 0.5\text{mm}$ ) for all materials wet up to their respective maximum hydration after the initial hydration event (Fig. 10). The fines for CB material retained the least amount of water with 69.3%, while no significant difference was observed between the PRB and PW with 77.5% and 80.4% respectively. At 25% IM both bark materials initially wet up similarly with 63.7% for PRB and 61.7% for CB, which was

much higher than the wood material which only retained 15.5% moisture after the initial event. All materials did gradually wet through hydration testing however wood did hydrate much more slowly than the bark materials (Fig. 11). Additionally wood fines retained the least amount of water after the 10 hydration events (57.6%) when compared to the CB fines (71.6%) and the PRB fines which held the most water (83.8%).

*Reengineered bark.* The CB and PRB materials were reengineered in order to have the same particle size distribution, consisting of 15% x-large, 35% large, 25% medium and 25% fine particles. At 50% IM both bark materials reached maximum hydration after 2 hydration events (Fig. 12). Bark processed at North Carolina State University held significantly more water throughout the hydration testing with 63.6% after 10 hydration events, while CB only held 47.9% water after testing (Table 7). At 25% IM PRB initially wet up more than CB at the same PSD with 23.9% and 17.9% respectively (Table 7). The commercially processed bark wet up much more slowly than PRB (Fig. 13) however both materials retained similar values after 10 hydration events (Table 7).

## **Discussion**

Differences observed in the whole materials at 50% and 25% IM with PRB and PW retaining more water (Fig. 1) than the commercially processed bark may be attributed to the considerably greater amount of medium and fine size particles found in these substrates (Table 1; Fig. 1).

Fine particles may not be what dominate the water retention characteristics of some organic based substrate components. Medium size particles for bark seemed the most

affected by moisture content i.e. more hydrophobic when compared to fines. Additionally these medium sized particles seemed to have a greater resistance to wettability compared to all other fractions. Considering the similarities between bark and wood materials at 25% IM for medium size particles (Fig. 9) and the differences observed in the fines at 25% IM (Fig. 11), inherent characteristics of the materials, particle size and moisture content may determine a materials hydrophobicity.

Wood material used in this study seemed to be driven more by fine particles than bark, as wood fines seemed to be more hydrophobic in nature than bark fines. Resistance to wettability for wood involved both the medium and fine particles while bark seems to be driven more by medium size particles than the fines. Fines in this study at 50% IM exhibited a greater difference between the two different bark materials than PW and PRB which were processed similarly (Table 6).

Bark materials processed commercially and at North Carolina State University hydrated significantly different at both 50% IM and 25% IM even at the same particle size distribution. Particle size distribution alone does not provide enough characterization of a organic substrate in order to determine its ability to capture and retain water.

Additional research on the wettability of similarly sized particles needs to be conducted. Wettability between like particle size materials i.e. from two different barks may be affected by their processing and cause significant alterations in their water holding and resistance to hydration. Testing of the hydration efficiency of materials processed in different ways but with similar specific surface areas would allow for a better understanding of where the effects of wettability lie within a particle size distribution for organic materials.

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Table 1. Volumetric water content of commercially processed bark (CB), raw pine bark (PRB) and pine wood (PW) processed at North Carolina State University and their particle size fractions X-large (>6.3mm) particles large (6.3 to 2.0mm) medium (2.0 to 0.5mm) fine ( $\leq 0.5$ mm) particles at 50% and 25% initial moisture content after an initial and after 10 hydration events.

<i>Whole material</i>				
Substrate	Process	Moisture content	Initial event	Final event
Bark	PRB	50%	55.9 a <sup>z</sup>	58.4 a
	CB	50%	34.4 c	36.4 bc
	PRB	25%	20.8 d	38.3 b
	CB	25%	17.5 d	31.2 c
Wood	PW	50%	48.2 b	58.5 a
	PW	25%	22.2 d	55.9 a
<i>X-large particles</i>				
Bark	PRB	50%	22.2 b	22.9 cd
	CB	50%	24.6 b	25.6 c
	PRB	25%	10.5 d	15.9 e
	CB	25%	15.9 c	20.6 d
Wood	PW	50%	33.1 a	39.0 a
	PW	25%	22.4 b	31.9 b
<i>Large particles</i>				
Bark	PRB	50%	30.3 a	32.5 b
	CB	50%	31.8 a	32.9 b
	PRB	25%	16.1 b	32.1 b
	CB	25%	13.5 b	23.2 c
Wood	PW	50%	34.8 a	45.7 a
	PW	25%	14.5 b	21.1 c
<i>Medium particles</i>				
Bark	PRB	50%	65.1 a	67.9 a
	CB	50%	51.8 b	55.9 b

Table 1. Continued

	PRB	25%	27.0 c	48.2 c
	CB	25%	25.3 c	47.7 c
Wood	PW	50%	45.4 b	66.4 a
	PW	25%	22.2 c	49.9 bc
			Fine particles	
Bark	PRB	50%	77.5 ab	77.5 b
	CB	50%	68.9 bc	69.3 c
	PRB	25%	63.7 c	83.8 a
	CB	25%	61.7 c	71.6 c
Wood	PW	50%	78.1 a	80.4 ab
	PW	25%	15.5 d	57.6 d

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<sup>z</sup>Means separated within column across all testing moistures and processing method by particle size using Least Significant Difference (LSD),  $P < 0.05$ . Means followed by the same letter are not significantly different.

Table 2. Volumetric water content for commercially processed bark (CB) as well as raw pine bark (PRB) processed at North Carolina State University at 50% and 25% initial moisture content after an initial and after 10 hydration events. Bark materials were reengineered in order to have the same particle size distribution<sup>y</sup>.

<i>Substrate</i>	<i>Process</i>	<i>Moisture content</i>	<i>Initial event</i>	<i>Final event</i>
Bark	PRB	50%	60.4 a <sup>z</sup>	63.6 a
	CB	50%	46.4 b	47.9 b
	PRB	25%	23.9 c	44.3 bc
	CB	25%	17.9 d	39.4 c

<sup>z</sup>Means separation between all materials by LSD, P<0.05. Means followed by the same letter in the same column are not significantly different.

<sup>y</sup>Particle size distribution of bark materials reengineered to: 15% X-large, 35% large, 25% medium and 25% fine particles.

Table 3. Particle size distribution of two differently processed pine bark materials and processed pine wood when oven dried and containing moisture<sup>z</sup>.

<i>Particle Size</i>	<i>Commercial bark</i>	<i>CB moist</i>	<i>Processed raw bark</i>	<i>PRB moist</i>	<i>Processed pine wood</i>	<i>PW moist</i>
X-Large <sup>y</sup>	21.2 a	22.7 a	13.2 b	14.7 b	4.2 c	5.4 c
Large <sup>y</sup>	44.5 a	47.0 a	29.4 b	31.5 b	47.1 a	46.9 a
Medium <sup>u</sup>	20.9 d	24.2 cd	27.0 bc	35.3 a	36.5 a	32.2 ab
Fines <sup>t</sup>	11.9 c	6.1 d	28.5 a	18.5 b	13.8 c	13.5 c

<sup>z</sup>Particle size distribution determined by sieving through column of sieves for five minutes in a shaker.

<sup>y</sup>X-Large Particles are larger than 6.3 mm in diameter.

<sup>x</sup>Values are means of percentages of total sample.

<sup>w</sup>Means separation between all materials by LSD, P<0.05. Means followed by the same letter the same row are not significantly different.

<sup>v</sup>Large particles are smaller than 6.3 mm and larger than 2 mm in diameter.

<sup>u</sup>Medium particles are smaller than 2 mm and larger than 0.5 mm in diameter.

<sup>t</sup>Fine particles are under 0.5 mm in diameter.

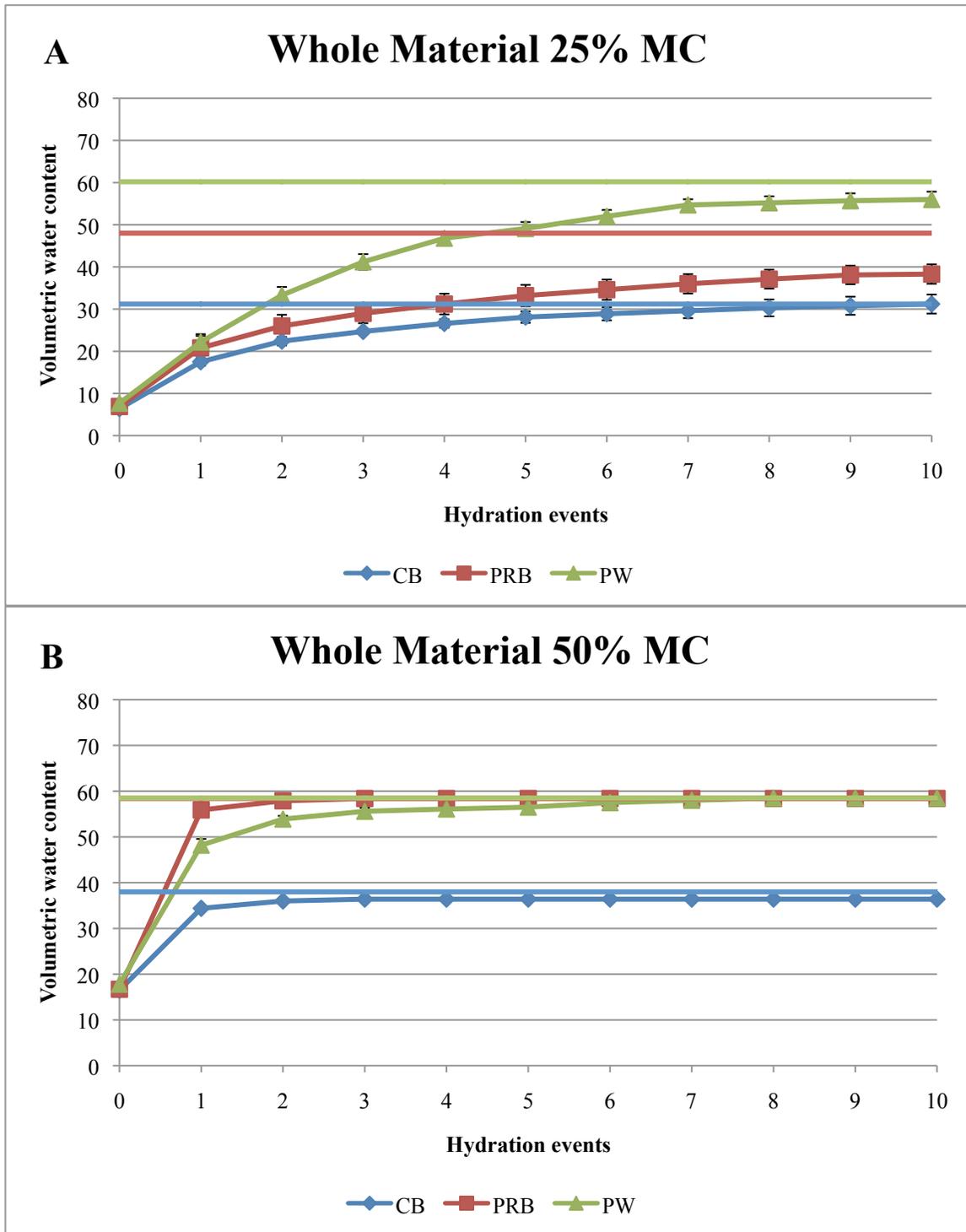


Figure 1. Wettability curves for commercially processed bark (CB) as well as raw pine bark (PRB) and pine wood (PW) processed at North Carolina State University and container capacity lines at A) 25% MC and B) 50% MC.

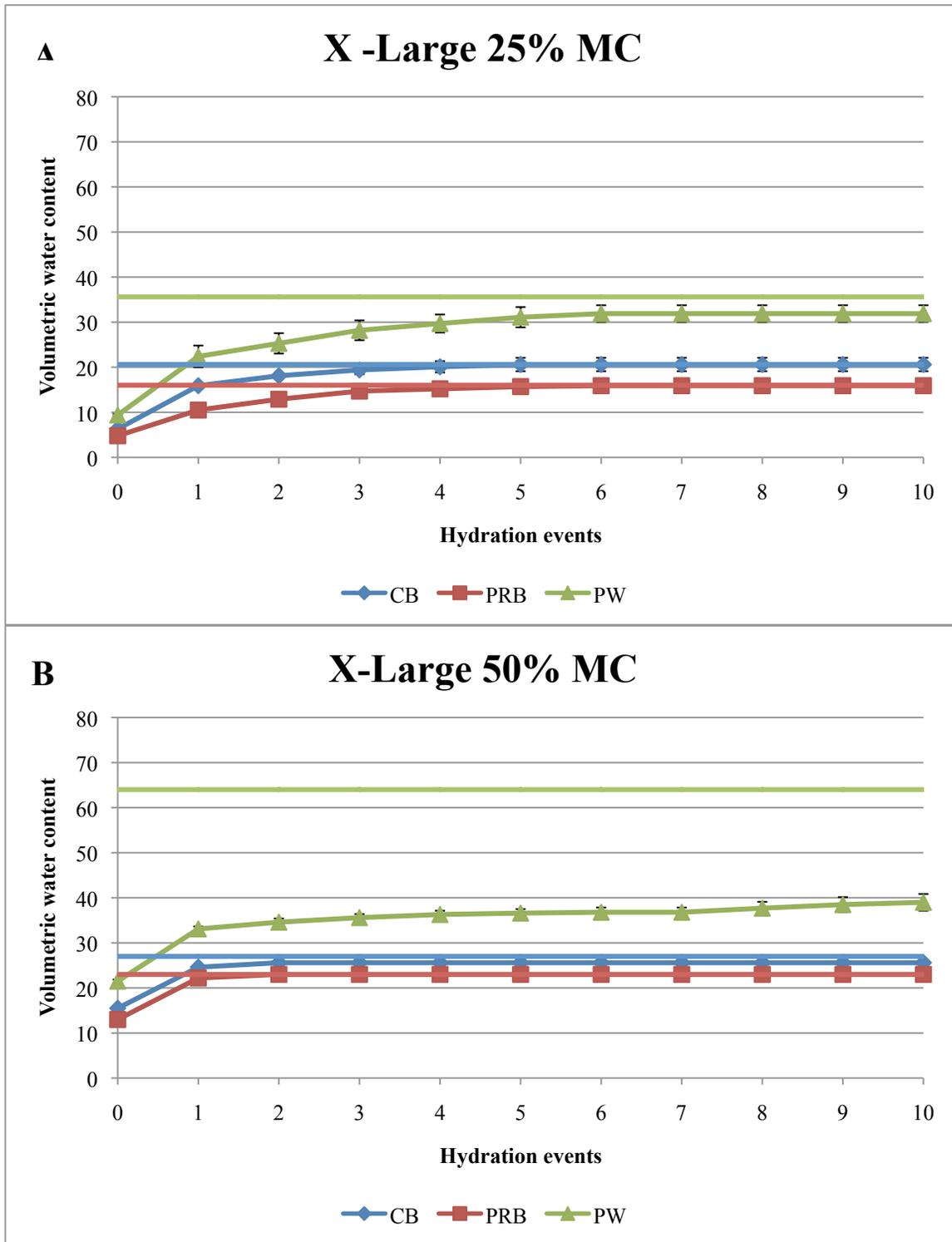


Figure 2. Wettability curves for X-large (>6.3mm) particles of commercially processed bark (CB) as well as raw pine bark (PRB) and pine wood (PW) processed at North Carolina State University and container capacity lines at A) 25% MC and B) 50% MC.

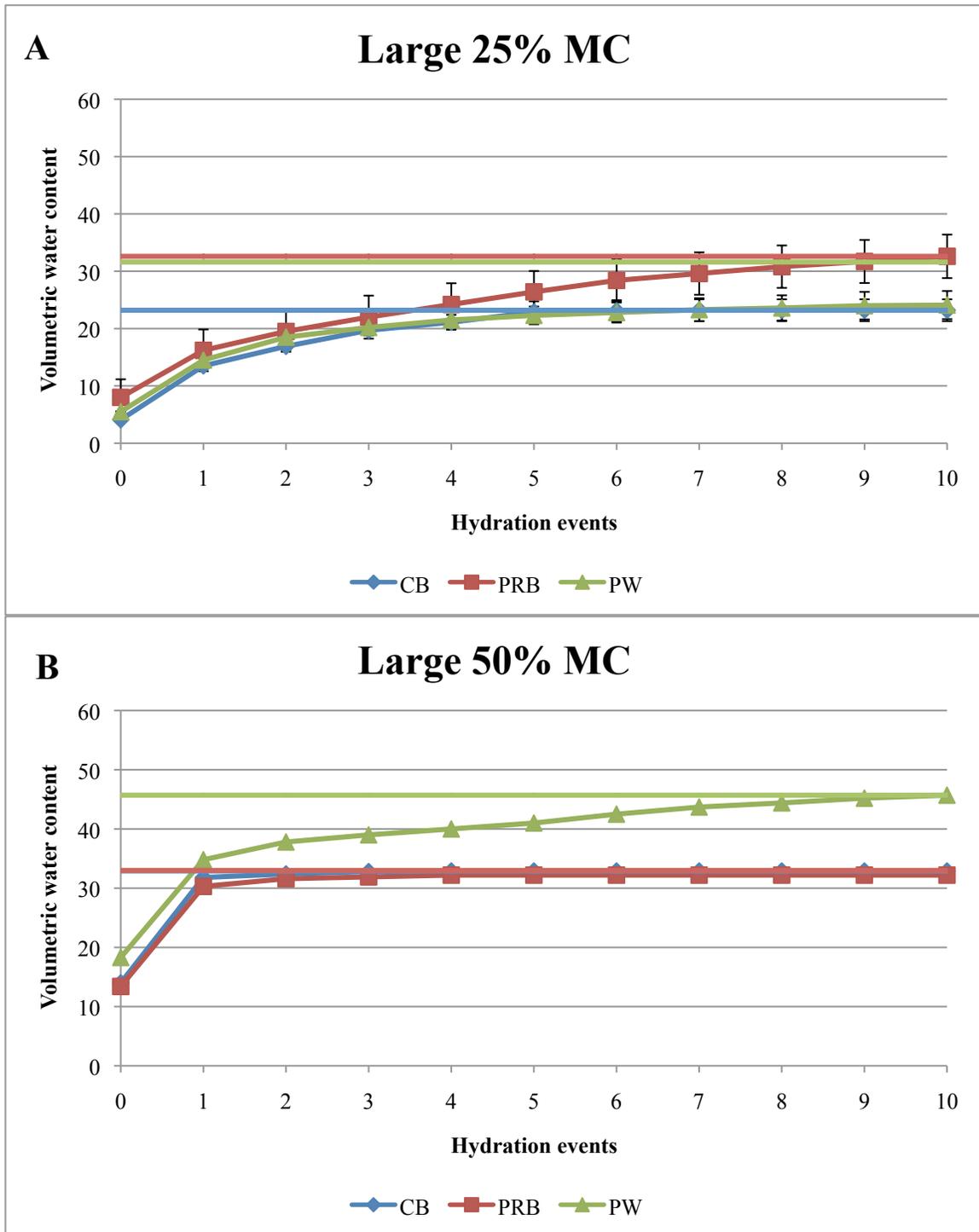


Figure 3. Wettability curves for large (6.3 to 2.0mm) particles of commercially processed bark (CB) as well as raw pine bark (PRB) and pine wood (PW) processed at North Carolina State University and container capacity lines at A) 25% MC and B) 50% MC.

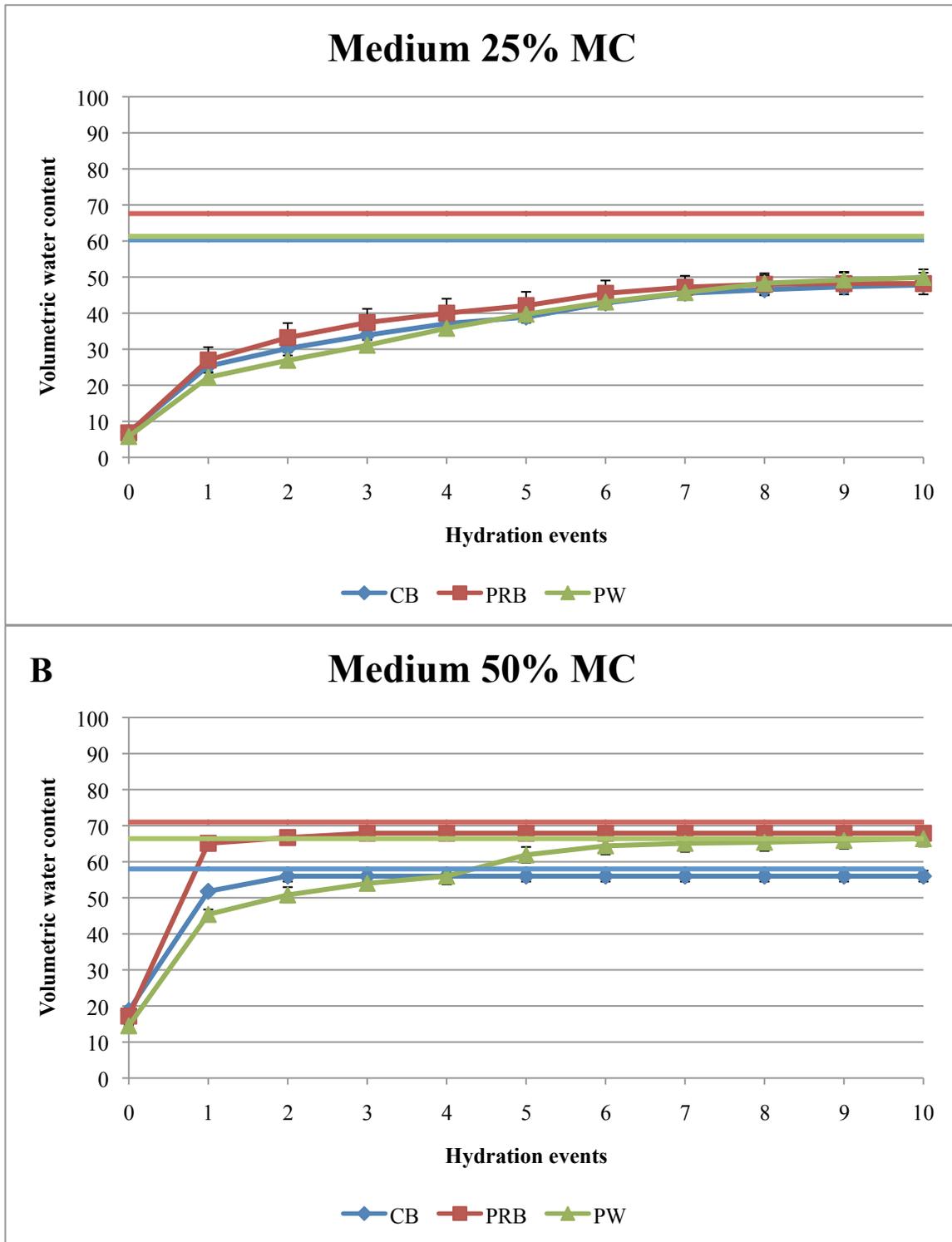


Figure 4. Wettability curves for medium (2 to 0.5mm) particles of commercially processed bark (CB) as well as raw pine bark (PRB) and pine wood (PW) processed at North Carolina State University and container capacity lines at A) 25% MC and B) 50% MC.

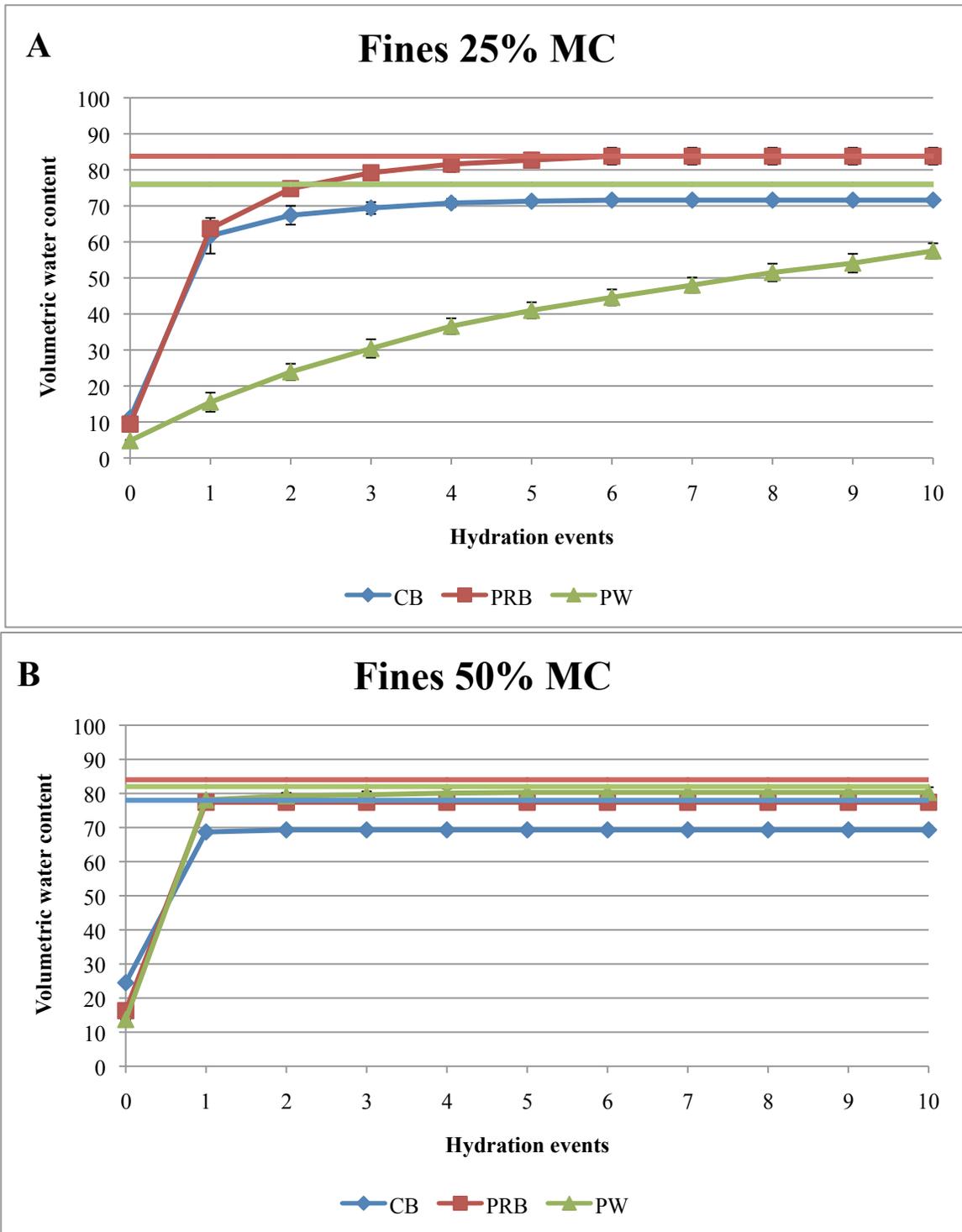


Figure 5. Wettability curves for fine ( $\leq 0.5\text{mm}$ ) particles of commercially processed bark (CB) as well as raw pine bark (PRB) and pine wood (PW) processed at North Carolina State University and container capacity lines at A) 25% MC and B) 50% MC.

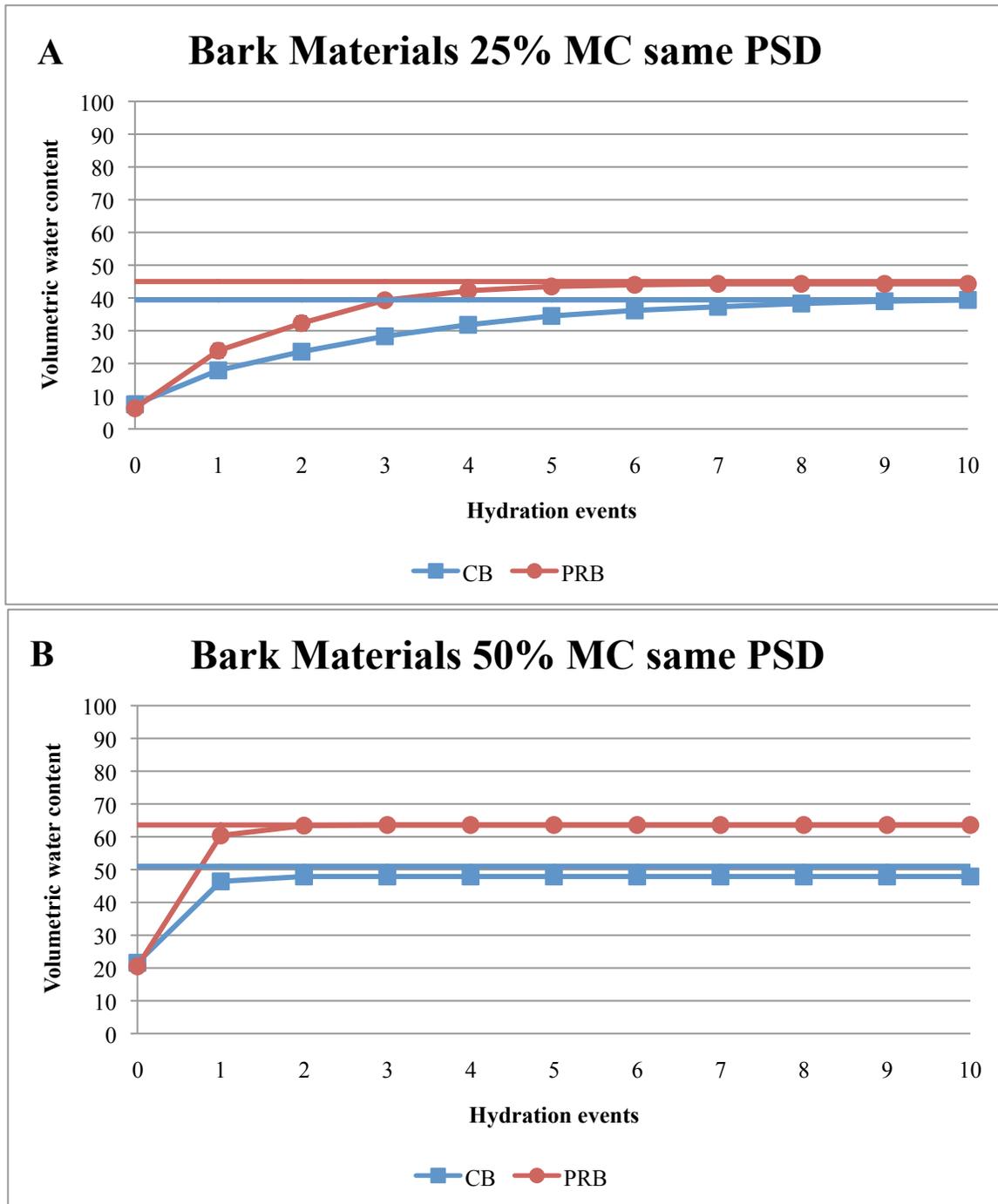


Figure 6. Wettability curves for commercially processed bark (CB) as well as raw pine bark (PRB) at North Carolina State University reengineered in order to have the same particle size distribution at 25% initial moisture content. Particle size distribution of bark materials reengineered to: 15% X-large, 35% large, 25% medium and 25% fine particles and container capacity lines at A) 25% MC and B) 50% MC.