A practical method for determining substrate capillary water sorption

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Abstract

The effectiveness of a horticultural substrate to capture (or absorb) and retain water through irrigation can be an important factor in a sustainable plant production system. Reduced substrate wettability can lead to less water captured, excessive leachate and poor plant growth. Taking into account hydraulic properties and substrate physical characteristics, hydration curves can be derived through subirrigation to understand the capillary uptake potential of soilless substrates. To better understand capillary potential, a low cost, practical system was developed to examine the relationship between wettability and hydration through subirrigation. Using ebb and flood subirrigaton, we developed hydration curves and calculated the rate at which water entered the substrate to determine the change in water uptake under specific treatment conditions. Experiments were conducted using Canadian sphagnum peatmoss, coconut coir, and aged pine bark under moisture contents ranging from 33 to 67%. The practical implications of this method span further than capillarity, also being used for determining substrate container capacity, the effect of irrigation pulsing regimens, and efficacy of wetting agent applications.

Keywords: wettability, water capture, growing media, substrate hydrology, subirrigation

INTRODUCTION

There is an evolution of production practices within the horticultural industry to increase sustainability. Irrigation efficiency and deficit are two major areas. An important part of this effort is to improve a substrate's ability to increase the amount of water absorbed by the substrate, and retain that water during specific irrigation practices. In essence, the better a substrate is at taking up water and making it available for plants to use, the less water is needed throughout a crop production cycle.

The amount of water sorption a substrate will express is always affected by how much, how long and in what manner water is delivered to the substrate during irrigation. This "exposure" to water must be taken into account to improve hydration efficiency. Hydration of substrates has been studied in two main areas: 1) "capacity" of water in substrates (Handreck and Black, 1984; Puustjarvi, 1974; Milks et al., 1989; Wallach et al., 1992) and 2) "intensity" of capacity expression, such as container geometry and wettability (Milks et al., 1989, Michel et al., 2001; Urrestarazu et al., 2008; Levesque and Dinel, 1977; Bilderback and Lorscheider, 1997; Fields et al., 2014). In other words, how much water can a substrate hold and in what condition the substrate is in to express that capacity.

These capacity and intensity conditions combine with irrigation parameters to determine how much water is literally "captured" with each and every irrigation event. So, it may be useful to think of water capture as the expression of the combination of these three areas. Previous work has examined water capture using surface applied water during drip irrigation (Fonteno et al., 2013; Fields et al., 2014; Schulker et al., 2020) The purpose of this work is to increase the measurement and understanding of water capture within horticultural substrates under specific subirrigation practices.

Performing irrigation events and determining water sorbed and retained by substrates, the approach should include simulated greenhouse irrigation methods. Through repeated irrigation events, a hydration curve can be generated to show how quickly the substrate was able to take up water and in what quantity (Fonteno et al., 2013). At the same time, the speed

Acta Hortic. 1317. ISHS 2021. DOI 10.17660/ActaHortic.2021.1317.38
Proc. II Int. Symp. on Growing Media, Soilless Cultivation, and Compost Utilization in Hort.
Eds.: B. Vandecasteele and J. Viaene

at which water is imbibed by the substrate could be quantified to improve the understanding of how repeated events may or may not be necessary for different substrate types and how container type/size can impact these variables.

Alone, this information is important, but the efficiency of water uptake is improved measured against a measure of maximum capacity of water that substrate can hold. The objective of this work was to develop a process to measure the capture and retention of water using subirrigation and to determine the effects of initial moisture content and intensity of hydrophobicity, on these parameters.

MATERIALS AND METHODS

The equipment for the subirrigation capillary unit follows the description from Schulker et al. (2020) consisting of a transparent cylinder, 5 cm i.d. × 15 cm h^{-1} with a mesh screen attached to one end, using rubber pressure plate rings (Soil moisture Equipment Corp., Santa Barbara, CA) and an Ebb and Flood irrigation unit (Hawthorn Hydroponics, Vancouver WA) 60.96 cm wide by 121.92 cm in length (Figure 1).

Water was introduced into this system via a faucet and controlled through a series of gate valves connected to the system. Water level was maintained at a continuous height with a flow rate of ~21 L min^{-1}. To be able to control the height of the water while also having a steady flow into the unit, a standing copper pipe was cut to allow water to be held at a height of 2.54 cm above the surface of the unit, or effectively allowing a 2.54 cm flooding height for the cylinders, at a steady state but can be held at any desired level within the parameters of the unit.

Blond sphagnum peatmoss (Premier Pro-Moss TBK, Quakertown, PA) was hydrated and fluffed to a preconditioned initial moisture content (IMC) of 70% (g g^{-1}). Peat was removed from the compressed bale and water was then added in 3-L increments, it was then agitated by hand to allow proper water absorption. Initial MCs were then measured using an Ohaus MB27 soil moisture determination balance (Ohaus Corp., Parsippany, NJ) to identify if further water additions were necessary. Two compressed bricks of coconut coir (Densu Coir, Ontario, Canada) were hydrated individually by adding 14 L of water (in 2 L increments), by hand, until the compressed brick was adequately broken apart. Moisture levels were then measured to determine further water additions needed to bring coir to an IMC of 70%. Loblolly (*Pinus taeda* L.) pine bark (Pacific Organics, Henderson, NC) which had been aged in outdoor windrows for four months and specifically engineered (hammer milled and screened) to have a container capacity (CC) of 55% volumetric water content (VWC) was tested, moisture levels determined, and further hydrated to 70% IMC.

All substrates were tested at three preconditioned initial moisture contents (IMC) of 33, 50, and 67% by weight (g g^{-1}). The sample cylinders were packed with each substrate component to have a bulk density (Db) within 5% of other samples of the same component. To achieve this, cylinders were filled with substrate (by weight) and then raised 12 cm off a flat surface, then tapped four times to bring the top of all 4 replications to a pre-measured line 10 cm from the base of the cylinder and 5 cm from the brim, representing 200 mL of substrate. Cylinders were then placed on an elevated mesh screen to optimize surface area exposure to water at about 1.7 cm off of the base of the flood unit.

Each water application is referred to as a hydration event. All hydration events tested were at a water height of 2.54 cm. Once the cylinders were placed on the mesh screen, the subirrigation unit was filled with water until it spilled over the top of the copper pipe, at that time water inflow was adjusted to equal outflow allowing constant height and flow of water. The substrates were held at a constant water level for 5 min to absorb water through flooding and capillary action. Once the 5 min event was finished, water was drained from the unit for one minute then each cylinder was weighed. The difference between the initial and final weight was the amount of water captured by the substrate during that hydration event. This procedure was repeated ten times to create the hydration curves.

After the final hydration event was completed and the cylinders were weighed, container capacity (CC) was then determined for each cylinder. The cylinders were returned to the ebb and flood unit (Figure 1) and CC was performed using a modified version of the NC

State University Porometer Method (Fonteno et al., 1995) as recorded in Schulker et al. (2020). Two kg aluminum weights were placed atop the cylinders to prevent tipping and buoyancy. The samples were then saturated from below, with a flow rate of ~15 L min^{-1}, into the unit until water reached 1/3 of the height of the cylinder (3 cm from the base of the cylinder). After two minutes, additional water was applied until reaching 2/3 of the height of the cylinder (6 cm). One final two-minute wait period and the water was applied until glistening on the surface of the substrate, totaling 10 cm from the cylinder base. Water was pumped into the system from below at intervals of 1/3 the height of the cylinder, waiting 2 min in between each filling until the substrate was full submerged in water. After saturating the system for 30 min, the water was drained, and samples were reweighed to record changes in weight (water capture and retention). Samples were then placed into a forced-air drying oven at 105°C for 48 h to dry, after which dry weights were measured and used to determine total water retained and IMC. Water absorption rate was calculated from the procedure described in Schulker et al. (2020) describing the amount of water, in mL min^{-1}, absorbed by the substrate in its first irrigation event and recorded in Table 1.

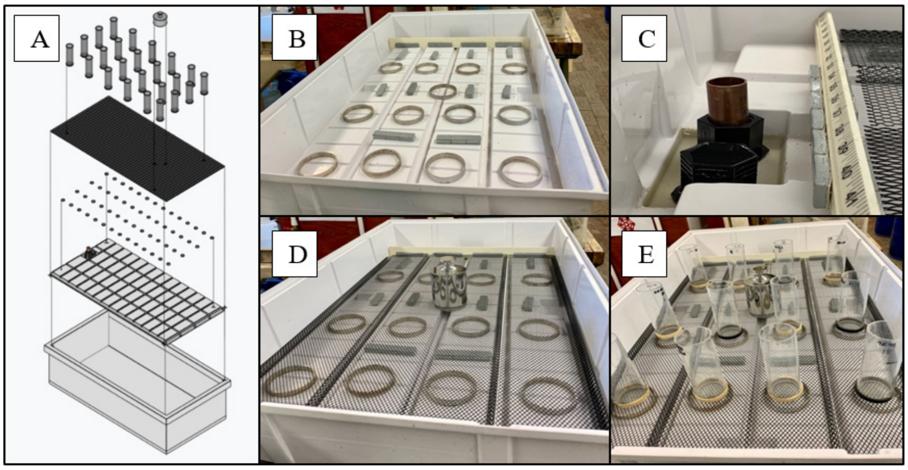

Figure 1. (A) Disassembled full system with (from top to bottom) the central weight, clear cylinders, mesh screen, steel rings, copper piping, and base ebb and flood unit. (B) Ebb and flood subirrigation unit with aluminum rings; (C) Copper piping used for water depth; (D) Mostly assembled system with mesh screen and 5kg weight; (E) Full assembled system with cylinders.

Table 1. Physical properties and performance of substrates through bulk density (D_b) in g cm^{-3}, total porosity (TP) in % volume and water absorption rate (AR) in mL min^{-1}, of coir, peat, and pine bark analyzed at three different moisture contents using subirrigation.

Subirrigation	Coir			Peat			Pine bark		
	D_b[a]	TP[b]	AR[c]	D_b	TP	AR	D_b	TP	AR
33% MC	0.10 a[d]	88.1 ab	10.94 a	0.15 a	87.1 a	0.58 b	0.15 b	80.1 b	8.37 ab
50% MC	0.09 a	91.1 a	12.86 a	0.13 a	85.9 b	1.24 b	0.19 a	83.0 a	9.10 a
67% MC	0.10 a	86.4 b	11.40 a	0.14 a	88.4 a	7.73 a	0.14 b	80.4 b	7.81 b

[a] D_b=the bulk density of the sample after testing at each moisture content.

[b] TP=is the percentage of substrate volume not occupied by solid particles; often calculated as TP=CC + AS.

[c] AR=the maximum rate in mL per min of water moving into the substrate during irrigation.

[d] Statistics using Tukey's honestly significant difference with alpha=0.05 are given down individual columns comparing moisture contents.

Particle size analysis was performed on three replicates of each substrate using 50-g oven-dried samples and a total of 6 sieves. These sieves ranged in size from greater than 6.3 mm to less than 0.063 mm plus a bottom pan to collect fine particulates. The sieves were placed into the RX-29 Ro-Tap sieve shaker (278 oscillations min^{-1}, 150 taps min^{-1}; W.S, Tyler, Mentor, OH). The sieves and pan were shaken for five minutes and the particle fractions retained on each sieve and the amount collected in the bottom pan (representing the smallest particle fractions) were weighed, with the results displayed in Table 2.

Table 2. Particle size distribution of three soilless substrate components.

Texture	Particle size distribution (%)[a]		
	Coir	Peat	Pine bark
Coarse[b]	6.8 C c[c,d]	19.4 B b	53.0 A a
Medium[e]	59.6 A a	40.0 A b	40.0 B b
Fines[f]	33.6 B a	40.6 A a	9.0 C b

[a] Particle size distribution calculated on a dry weight scale using means of three oven-dried samples.

[b] Coarse=particles that are greater than 2.0 mm in diameter.

[c] Values are means of percentages of the total sample.

[d] Statistics are determined down columns (denoted by an uppercase letter) and across rows (denoted by a lowercase letter) using Tukey's honestly significant difference to determine similarities and differences across all components.

[e] Medium=particles that are less than 2.0 mm but greater than 0.5 mm in diameter.

[f] Fines=particles that measure less than 0.5 mm in diameter.

RESULTS AND DISCUSSION

It should be noted that the IMCs for this experiment of 33%, 50%, and 67% were all determined by weight (g g^{-1}). This is the industry standard and essential when bulk materials are tested. The hydration curves were constructed by volumetric water content (VWC) to describe the amount of water capture by the substrate. With that said, the IMC of 50% by weight was actually 9 to 11% by vol for coir. For peat, the IMC of 50% by weight ranged from 12 to 15% by vol, and for pine bark the range was from 16 to 18% by vol. These differences represent the density differences between the three substrate materials. As for particle size, coir represented the substrate with the highest percentage of particles below 2.0 mm in diameter, representing 93.2% of all particles tested while pine bark showed the highest percentage of coarse particles at 53.0%. Peat occupied a middle ground between pine bark and coir with 12.6% more coarse particles than coir, but still 33.6% less than that of pine bark.

Using values taken from the hydration curves, three specific values were compared to better understand effective water capture (Table 3). H_1 represented the first irrigation event (one 5-min event), H_{10} represented the final irrigation event (after 10 5-min events equaling 50 total minutes of irrigation), and CC. To normalize the data to examine the effects of IMC on capture, the IMC was subtracted from H_1 and H_{10}. Bulk density, total porosity, and water absorption rate are all given in Table 1 to show more of the properties of the substrates during testing, and the rate at which water was imbibed by the substrate.

Coir

The hydration curves for coir (Figure 2A) indicated a pattern related more directly toward IMC. The first hydration event accounted for the most water absorbed by the substrate compared to all other events. At all IMCs, coir was able to capture water, but the intensity at which it did was based on the moisture level of the substrate. As IMC increased, the volume of water absorbed by coir increased (denoted by H_1 and H_{10}). Once IMC was subtracted from the total VWC, the data shows a very different story (Table 2). Coir had taken up nearly the same (~2%) amount of water at all moisture levels, with 33% IMC recording the greatest water captured at H_{10}. With this information, it is evident that the major difference shown in Figure 2a is the water captured through the preconditioning process of coir.

Table 3. Effective water capture, first hydration (H_1), final hydration (H_{10}) and container capacity (CC), of coir, peat, and pine bark analyzed at three different moisture contents using subirrigation.

Moisture	Coir				Peat				Pine Bark			
	H_1[a]	H_{10}[b]	CC[c]	S*[d]	H_1	H_{10}	CC	S*	H_1	H_{10}	CC	S*
33% IMC	25.2 b	41.5 a	75.4 ab	L** Q*	2.9 b	9.5 bc	49.8 bc	L** Q*	22.8 b	30.3 ab	57.5 a	L*** Q*
50% IMC	28.4 a	40.9 a	76.1 b	L* Q*	5.0 b	16.5 b	56.5 b	L* Q*	31.5 a	33.1 a	59.3 a	L* Q*
67% IMC	29.4 a	33.8 b	78.7 a	L* Q*	24.9 a	32.8 a	77.0 a	L* Q*	25.2 ab	26.9 b	58.1 a	L* Q*

[a] H_1=the amount (by volume) of water that is absorbed after one irrigation event minus the initial moisture content.

[b] H_{10}=the amount (by volume) of water that is absorbed after the final hydration event minus the initial moisture content.

[c] CC=maximum volumetric moisture content attained by sample.

[d] Significance (S*): linear (L) and quadratic (Q) regression significance test, NS=nonsignificant, ***P≤0.001, **P≤0.01 *P≤0.05 down all columns for peat, coir, and pine bark.

Peat

Under low moisture conditions, peat absorbed less water than coir at treatments of 33 and 50% IMC. At 33% IMC, peat captured ~23% less water than coir under the same treatment (Table 2). The intensity of hydrophobicity was an important factor in the amount of water captured by peat, limiting the amount of water being imbibed by the substrate at both 33 and 50% IMC. As IMC increased, water capture also increased, with a 21% increase at H_1 and H_{10} from 33 to 67% IMC (Figure 2B). Unlike coir, the subirrigation testing revealed a variable CC in peat based on IMC, from as low as 49.8% VWC at 33% IMC up to 77% VWC at 67% IMC.

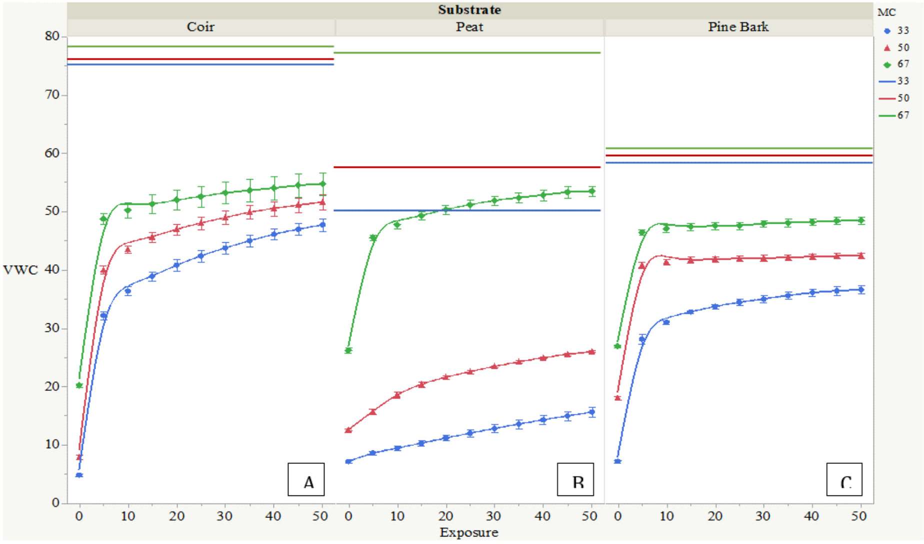

Figure 2. Substrate hydration curves for coir, peat, and pine bark over ten hydration events at three initial moisture contents through subirrigation. With (A) representing coir, (B) representing pine bark and (C) representing peat. The moisture contents are as follows: 33% (blue), 50% (red), and 67% (green) with the corresponding container capacities displayed as same-colored bars.

Pine bark

As with both peat and coir, pine bark increased water capture as IMC increased from 33 to 50%, but seemingly peaked at 50% and reduced capture at 67% IMC. Larger particle size and pore structure helped equate to a linear increase shown in the hydration curves (Figure 2C), while subtracting the initial moisture from the VWC values in Table 2 show that pine bark captured ~85% of all water at H_1. At 67% IMC, the bark both captured less water at H1 and H_{10}, but also has a lower CC than 50% IMC. The CC of pine bark is consistent, regardless of treatment with only ~10% difference between the lowest and highest recorded CCs.

The mesh screen and aluminum rings were implemented in the system to maximize the lower surface area exposure to water. A similar method, the RHP Wok Method is used to rate substrates moisture characteristics by allowing 24 h for water to be imbibed by the material at less than 2 mm of depth (Geuijen and Verhagen, 2017). This removes the increase in water capture by flooding and uses only the substrates capillary properties to capture water. The capillary system has the ability to test materials at any desired water level, duration (time), pulsing rate, and with (or without) wetting agents in either the substrate or the water.

Using data from this procedure (Tables 1 and 3; Figure 2), we may make the following observations about the behavior of water capture and retention in these materials. Coir had little limitation in hydrating under all treatment conditions, with water capture increasing as IMC increased. Peat was impacted by the intensity of hydrophobicity under lower moisture conditions and did not make significant gains in water capture until 67%. Lastly, pine bark increased water capture as IMC increased, with a smaller margin between the first and final hydration event water capture at 67% IMC. Both coir and pine bark were the only two substrates to reach 50% of their respective CC once the initial moisture was deducted. Peat, even with a variable CC based on IMC, did not capture more than 42% of the CC.

The results shown by peat, coir, and pine bark were designed to give a broad understanding of the way these materials respond to irrigation under specific conditions. Typical potting moisture is recommended at 50% moisture, but from this experiment we were able to show that peat at that moisture was not as effective in taking up water as other materials. The same is true at 33% IMC, where both coir and pine bark were able to absorb water, peats capture ability was heavily reduced volumetrically, and again shown in its absorption rate (Table 3). While 67%, albeit on the higher end of the spectrum and nearly at container capacity for pine bark, represented the best that peat was able to capture. The three moisture level treatments are meant to show a substrates response to infrequent watering compared to frequent watering, and its impacts on water captured.

This procedure is simple and cost effective. A multitude of materials can be tested in this system, the equipment is versatile, and the procedure itself can take less than 2 h (depending on the amount of sample being tested). What is not shown in procedure is the potential for use and application of wetting agents, measuring total porosity, and the ability for stratification of the cylinders for experimentation. For this study we decided to use one water level, three substrates, three moisture contents and one time interval while also identifying H_1, H_{10}, and CC. Those parameters may be configured differently to test substrates under different preconditioning treatments, however H_1, H_{10}, CC, and the hydration curves all show particularly useful comparisons when characterizing substrate capillary properties and potential when using subirrigation. This process shows, in a short period of time, the capillary potential of a substrate and the rate at which water can be captured. Thus, showing when the majority of water is captured during irrigation to then tailor irrigation practices to fit the performance of each material.

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