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Quantifying the Sorptive Behavior of Traditional Horticultural Substrate Components Based on Initial Hydraulic Conditioning

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Abstract. **The ability of a substrate component (organic or inorganic) to capture and retain water (hydration and wettability) is important to investigate and promote water-use–efficient practices. Many factors may play a role in the wettability of the material, including the processing of the material and its initial handling. The goal of this experiment was to determine the effect of moisture content (MC) on the sorptive behavior of substrates after an initial and secondary hydration cycle. Coir, peat, and aged pine bark were evaluated at a 33%, 50%, and 66% MC by weight. At all moisture levels, coir and bark were minimally affected by MC or the initial hydration cycle. Peat was the most vulnerable to changes in sorptive behavior as a result of wetting and drying cycles. After a wetting and drying cycle, the maximum volumetric water content of peat from surface irrigation was reduced 21.5% (volumetrically), more than three times any other treatment. The hydration efficiency of peat was improved when blended with as little as 15% coir. These experiments provide evidence that MC and initial handling of the substrate can lead to differences in initial water use efficiency.**

The characteristics of horticultural substrates are important factors in determining efficient irrigation practices in container plant production. 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). The ability of a substrate to retain and distribute water influences the necessary irrigation rate and frequency during plant production (Nash and Pokorny 1992). As regulatory efforts focus on water conservation, growers specializing in container plant production must understand how substrate characteristics influence water use.

Irrigation efficiency in container plant production is influenced by several factors. Two established metrics are container capacity (CC) and wettability (Fields et al. 2014; Handreck and Black 1984; Michel et al. 2001; Milks et al. 1989). CC is the maximum amount of water a substrate can retain after drainage. This is typically determined by wetting the substrate slowly from the bottom and then allowing it to drain (Fonteno et al. 1995). Wettability describes the capacity of the substrate to capture and distribute water spatially, either from an overhead irrigation or subirrigation application (Fonteno et al. 2013). Several factors are known to influence the CC and wettability of a substrate, such as moisture content (MC), hydrophobicity, the direction of water application, and preferential flow (Dekker and Ritsema 1994; Fields et al. 2014; Michel et al. 2001). Although phenomena such as preferential flow have been challenging to quantify, the effects of substrate MC and hydrophobicity have been well studied (Fields et al. 2014; Fonteno et al. 2013; Schulker et al. 2020). In general, these studies have established that as substrates dry, their hydrophobicity can intensify. In mineral soils, changes in wettability are attributed to organic residues and hysteresis (Dekker and Ritsema 2000; Jouany et al. 1992). Because the dominant constituents of horticultural substrates are organic, degradation and pore deformation during wetting and drying cycles can have considerable sorptive effects (Beardsell and Nichols 1982; Michel et al. 2001).

The initial handling of a substrate component, whether for analytical or commercial purposes, can alter its hydration efficiency significantly (da Silva et al. 1993). For example, analytical techniques such as the North Carolina State University (NCSU) Porometer Method (Fonteno et al. 1995) require specific MCs for different substrates to be tested accurately. Pine bark is generally shipped by truckload and may vary considerably in MC. Peat moss is commonly packaged and shipped in dry bales at a 2:1 compression and needs to be reconstituted mechanically before being used. Similarly, coconut coir is shipped primarily in a 5:1 compressed brick form and requires the addition of water to aid in fluffing and reconstituting the material before use. Because different materials are handled and shipped in a variety of ways, their packaging, initial MC, and handling when received may influence their wettability.

Therefore, the objective of this study was to quantify the sorptive effects on substrate wettability and water holding capacity. Inferences into the effectiveness of the substrate to capture water have been difficult to demonstrate statistically. To assist in this, we used a monomolecular exponential model to quantify water holding capacity and the irrigation volume required to reach that capacity. Because the wetting behavior of peat can be greatly affected by hydrophobicity, a second objective was to determine the effectiveness of hydrophilic coconut coir in mitigating the initial hydrophobicity of a peat substrate.

Materials and Methods

Substrates. The substrate materials tested were a 6-month aged loblolly pine bark (*Pinus taeda* L.; Pacific Organics, Henderson, NC), sphagnum peatmoss (BP; Berger, Saint-Modeste, Quebec, Canada), and coconut coir (Densu Ventures, Ontario, Canada). The initial MC (by mass) of each material was determined by weighing three 200-mL samples of each substrate, oven drying at 105 °C for 24 h, and reweighing. The initial MC of the peat in the bale was 38%. Pine bark was received at an MC of 55%. Coconut coir, compressed in brick form, had an initial MC of 15%.

Hydration process. Each substrate component was evaluated at three MC levels after an initial and second hydration cycle (HC 1 and HC2, respectively). By weight, the three MC levels evaluated for each substrate were 33%, 50%, and 67%. These levels were not selected

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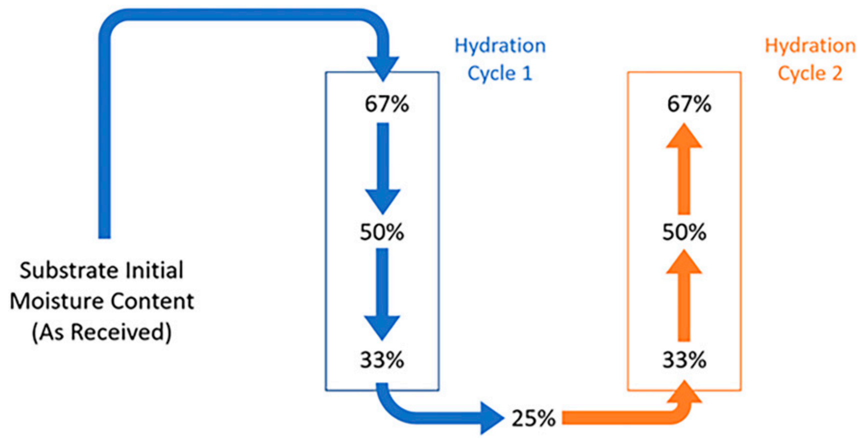

Fig. 1. A flow chart depicting the wetting up and drying down cycles of substrates evaluated in this study. The wettability of each substrate was tested at each moisture content framed within hydration cycles 1 and 2.

arbitrarily, but were determined by mass wetness—a measure of the weight of water per gram of substrate. The recommended MC level for potting soils is 50% by weight or a mass wetness of 1.0 $g \cdot g^{-1}$. The two additional MC levels evaluated, 33% and 67%, were determined at half (0.5 $g \cdot g^{-1}$) and double (2.0 $g \cdot g^{-1}$) the recommended mass wetness level, respectively. To quantify the sorptive effects induced by the initial wetting and drying cycles, substrate samples were hydrated to an MC of at least 75% and sealed within 55-L plastic bags for 24 h to equilibrate. After the equilibration period, 300-mL samples of each substrate were spread 4 cm deep on a tray and allowed to air-dry to the target MC. After the target MCs were reached, the samples were placed back into plastic bags, sealed, and allowed to equilibrate over 24 h. Samples prepared and collected during this initial hydration and drying cycle were classified as HC 1 samples. HC 1 samples reached their respective moisture levels through desorption by drying from a previous higher level. Additional samples were allowed to continue to dry to an MC of 25% before being rehydrated in HC 2. In HC 2, the samples were brought back to the same hydration levels as in HC 1, bagged, sealed, and allowed to equilibrate over 24 h. HC 2 treatments gained their final treatment values through an absorptive addition of water. To visualize the process used to prepare these samples, a flow diagram of the procedure is presented in Fig. 1. Throughout the testing, moisture levels on all samples were checked using an MB 27 soil moisture balance (Ohaus Corp., Parsippany, NJ).

Particle size distribution (Table 1) was performed on three 100-g dried samples of each substrate to characterize the materials into four commonly used fractions. Samples were dried at 105 °C for 48 h, distributed across the top sieve, and agitated in a RX-29 Ro-Tap sieve shaker (278 oscillations/min, 150 taps/min; W.S. Tyler, Mentor, OH) for 5 min. The sieve sizes used were 6.3, 2.0, and 0.5 mm, and the bottom pan collected fines. The particle fractions retained on each sieve and in the pan were collected and weighed.

Wettability. To determine the sorptive effects on substrate hydration efficiency with surface-applied irrigation, this experiment followed the wettability procedure described in detail by Fonteno et al. (2013), Fields et al. (2014), and Schulker et al. (2020). To summarize, substrate samples were packed into transparent cylinders (5-cm internal diameter × 15 cm in height). The total volume of substrate packed in each cylinder was 200 cm^3. Ten irrigation events of equal volume (200 mL) were then diffused evenly across the substrate surface. The effluent volume was measured and recorded after each irrigation event. The water retained was calculated by subtracting the amount of water applied (200 mL) from the amount of effluent captured. Each water capture event was expressed as the third hydration measure of volumetric water content (VWC), or the percentage of the container volume containing water. After the final irrigation event was complete and final weights were taken, CC was then determined for each cylinder by transferring the samples carefully into NCSU Porometer funnels, saturating the samples via subirrigation, and draining the funnels/samples of free water. With three substrates, three MC levels, two hydration processes, and four reps, there were a total of 72 experimental samples.

Substrate blends. To look at the mitigation of hydrophobicity in peat using a hydrophilic component, three peat–coir mixes of 85:15, 70:30, and 55:45 peat:coir (vol:vol) from the same sources were prepared and tested using the same methods described earlier. These blends were tested as a result of observing a significant difference in peat and coir at a 50% MC between HC 1 and HC 2. The addition of varying percentages of coir to a peat-based mix was conducted to observe how a naturally occurring hydrophilic material such as coir might alter the sorptive properties of a potentially hydrophobic peat material.

Statistics. Quantifying the elements or characteristics of a wettability graph is challenging. Often, the data resemble a plateau model. The VWC of the samples increases rapidly during the first few irrigation events, but gains typically diminish by the final irrigation event. Previous attempts to characterize hydration efficiency numerically have used the VWC at the first and final hydration event, the mean irrigation event where the plateau (no additional water uptake observed) occurs, and CC (Fields et al. 2014; Schulker et al. 2020).

Table 1. Particle size distribution of three horticultural substrate components.

Texture[i]	Substrate component[ii] Coir	Peat	Pine bark
Extra-large	0.1 c[iii]	6.4 b	21.2 a
Large	9.9 c	43.1 b	44.5 a
Medium	47.7 a	35.1 b	20.9 c
Fines	43.1 a	22.1 b	11.9 c

[i] Particle size distribution was determined by sieving through a column of sieves for 5 min in a shaker. The texture of the substrates was classified by size. Extra-large particles were retained in a 6.3-mm-aperture sieve. Large particles passed a 6.3-mm screen and were retained in a 2-mm-aperture sieve. Medium particles passed a 2-mm screen and were captured in a 0.5-mm aperture sieve. Fines were particles that passed a 0.5-mm-aperture sieve and were retained in the pan.
[ii] Values reported are the percentage average mass retained in each texture class of the initial sample mass.
[iii] Means separation between substrates within each texture class by least significant difference, α = 0.05. Means followed by the same letter within the same row are not significantly different.

Monomolecular exponential (growth) models describe the process of a simple, irreversible first-order chemical reaction. For example, when used for a disease in plants, the model assumes the maximum level of disease is 100% and that diseased plant tissue must lie between 0% and 100%. The rate of change is proportional to the healthy tissue of the plant. For substrate wettability, the minimum and maximum VWC are known, but the values are often not 0% or 100%. Instead, the modeled data include the initial substrate VWC and the maximum retained VWC after 10 irrigation events (assuming a maximum is reached). The rate of change is proportional to the water retention of the substrate. By using a monomolecular exponential model, wettability data can be fitted accurately and the irrigation volume required to reach an effective maximum water holding capacity can be derived. The model is as follows:

$$\mathrm{VWC} = Y_M - (Y_M - Y_0)\exp^{(-kI_n)}, \quad [1]$$

where VWC is the predicted volumetric water content, Y_M is the maximum obtainable VMC, Y_0 is the initial VWC of the substrate, k is the relative rate of VWC increase as the number of irrigation events increases, and I_n is the irrigation event number (1–10). The VWC of the substrates recorded at irrigation event zero represent the percent VWC of substrates at each MC level. Therefore, an MC of 50% (by weight) had a volumetric water content of 12% to 15% v/v (moisture) for peat. For coir, an MC of 50% ranged from 9% to 11% v/v, and for pine bark, 16% to 18% v/v. To quantify more completely the amount of water required to reach the retention capacity of the substrate, irrigation events were expressed by

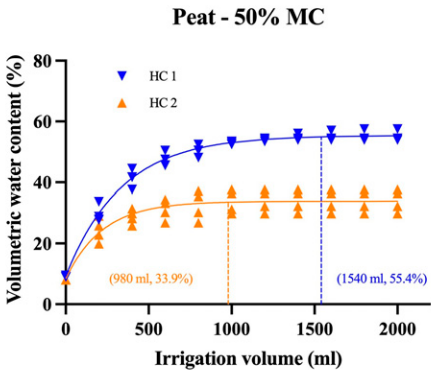

Fig. 2. The volumetric water content capture rates for peat at 50% moisture content (MC) following an initial hydration cycle (HC 1) and a second hydration cycle (HC 2). Data points were modeled to derive the intercept at which 99% of the maximum volumetric water content was achieved.

cumulative irrigation volume (one irrigation event = 200 mL). Using a derivative of Eq. [1], the intercept at which the substrate approached its maximum water retention was determined. The derivative equation is as follows:

$$I_V = \frac{-1}{k\log\left(\frac{Y_M - 0.99Y_M}{0.99Y_M - Y_0}\right)}, \qquad [2]$$

where I_v is the cumulative irrigation volume. Because the model is asymptotic, the maximum obtainable VWC (Y_M) is never reached. Instead, 99% of Y_M was used to calculate the irrigation volume intercept. For example, Fig. 2 is a combination plot depicting the wettability data points and model line for peat at a 50% MC during HC 1 and HC 2. The irrigation volume required to reach 99% of the maximum VWC for HC 1 was 1540 mL and was 980 mL for HC 2.

Intercept and CC data were collected for each experimental unit. Data were analyzed using PROC NLIN and PROC GLIMMIX (version 9.4; SAS Institute, Cary, NC). Least significant means were separated by the least significant differences at $P \leq 0.05$. Multiple comparisons were adjusted by a Tukey's honestly significant difference test. This test determined the similarities and differences in irrigation volume, VWC intercept values, and CC across substrates; MC levels; and hydration cycles.

Results

Coir. The wettability curves for coir (Fig. 3A–C) indicated few differences by MC level or HC. Across all MC levels and HCs, coir had greater VWCs than all other substrate treatments (Table 2). MC levels had little influence on the maximum VWC of coir from overhead irrigation. The maximum VWC from the desorption cycle (HC 1) was an average of 5.2% greater than the adsorption cycle (HC 2). However, because of the variability in the data, these differences were not consistently significant. Coir was efficient at approaching or reaching its CC from surface irrigation with all treatment combinations. The average volume of irrigation required to reach its maximum VWC increased as the initial MC decreased (Table 3). Although it required almost double the irrigation volume on average to reach 99% of the maximum VWC, there were no

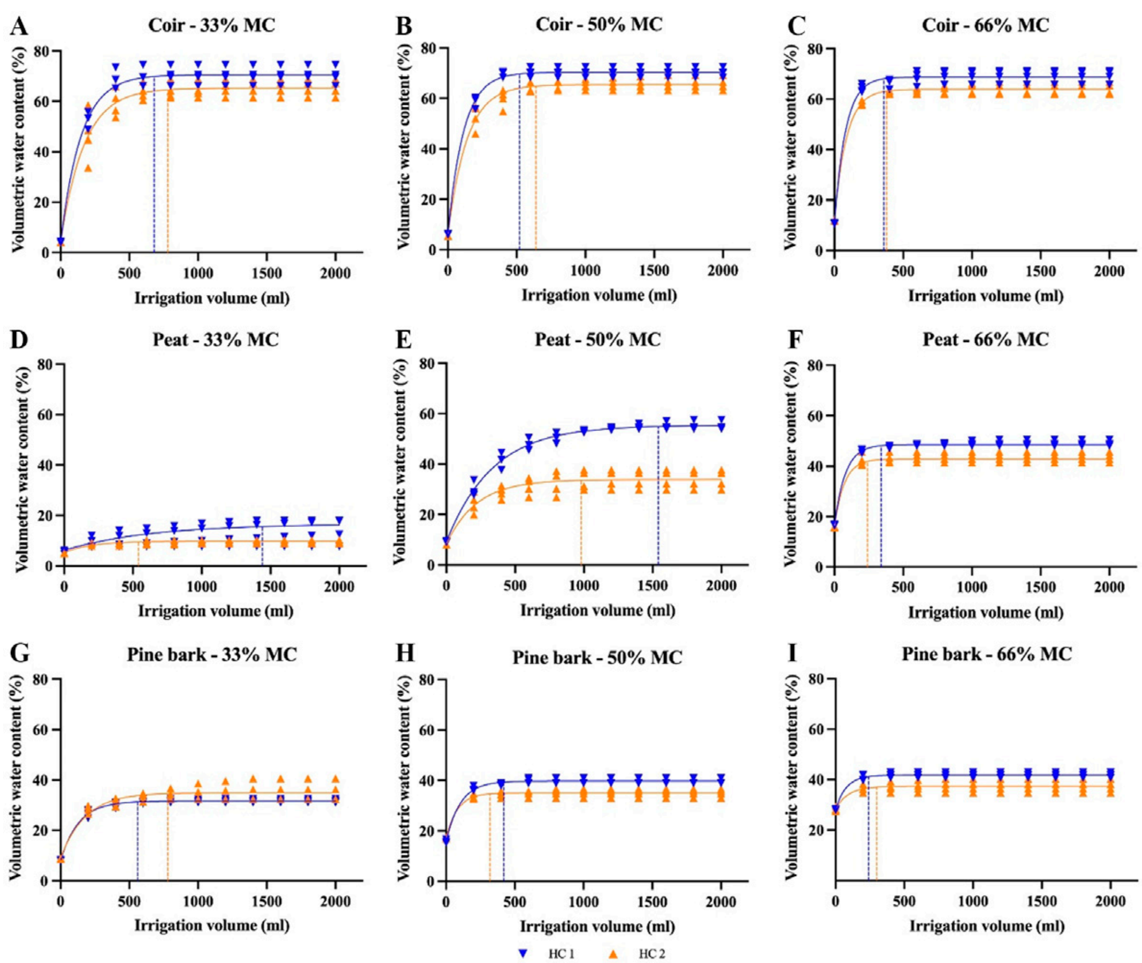

Fig. 3. The volumetric water content capture rates for coir (**A–C**), peat (**D–F**), and pine bark (**G–I**) at 33%, 50%, and 67% moisture content (MC) following an initial hydration cycle (HC 1) and a second hydration cycle (HC 2). Data points were modeled to derive the intercept at which 99% of the maximum volumetric water content was achieved.

Table 2. The volumetric water content of three substrate components prepared at three moisture contents following two wetting and drying (hydration) cycles (HC 1 and HC 2).

	Substrate moisture content[i]								
	Coir			Peat			Pine bark		
Variable	33%	50%	67%	33%	50%	67%	33%	50%	67%
HC 1[ii]	70.6 ab[iii]	70.4 ab	68.8 a–c	14.4 op	55.4 d	48.6 ef	31.7 l–n	39.8 h–j	41.8 g–i
CC[iv]	70.2 a–c	70.0 a–c	72.0 a	47.0 fg	57.0 d	55.0 d	31.0 mn	36.7 i–l	41.7 g–i
HC 2[v]	64.5 bc	65.6 bc	64.0 c	9.4 p	33.9 m–k	43.5 f–h	37.4 i–k	35.1 j–n	35.0 fg
CC[iv]	67.0 a–c	68.0 a–c	67.0 a–c	17.0 o	52.0 de	54.0 d	36.4 i–m	39.9 i–j	35.5 i–m

[i] The maximum percentage (by volume) of water retained by the substrate.

[ii] For HC 1, materials were received "as is" and hydrated to > 75% moisture content (by weight) before drying down to either 33%, 50%, or 67%. Surface irrigation was applied in ten 200-mL events to determine water retention.

[iii] Statistics using Tukey's honestly significant difference with $\alpha = 0.05$ are given throughout the table. Means with the same letter are not statistically different.

[iv] The container capacity (CC) is the maximum volumetric water content attained by the sample after saturation.

[v] For HC 2, materials were received, hydrated, dried to a 25% moisture content, and then rehydrated to either 33%, 50%, or 67% before testing. Surface irrigation was applied in ten 200-mL events to determine water retention.

differences between the 67% and 33% MC levels because of the variability in the data.

Peat. Contrary to coir, wettability curves for peat identified patterns related to MC level and HC (Fig. 3D–F). From maximum to minimum VWC and intercept irrigation volume, peat had the most variability by substrate (Tables 2 and 3). In general, as the initial MC decreased, water retention decreased. The lowest VWC was recorded in peat at the 33% MC level. Surprisingly, peat at a 50% MC during HC 1 had the highest VWC of peat treatments (55.4%), but required the most irrigation volume (1540 mL) to reach that level. The greatest difference in sorptive behavior was observed in peat at a 50% MC. Between HC 1 and HC 2, the maximum VWC of peat from surface irrigation was reduced by 21.5% (volumetrically), more than three times any other treatment. The difference in maximum to minimum irrigation volume required to reach maximum water retention was 1300 mL—the equivalent of 6.5 irrigation events, more than twice the variability of coir or pine bark. For most peat treatments, CC was not reached after 10 surface irrigation events.

Pine bark. The wettability curves for pine bark across all treatments were more consistent than peat. Bark contained the greatest percentage of coarse particles, which could have affected its maximum water retention (Table 2). Few differences were observed across MC levels or HCs. The highest VWC (41.8%) and the lowest (31.7%) for bark was recorded in HC 1 at a 67% and 33% MC, respectively. Although the average maximum VWC decreased between HC 1 and HC 2 at 50% and 67% MC levels, bark showed little change in sorptive behavior. Bark was efficient at approaching or reaching its CC from surface irrigation with all treatment combinations. As MC decreased, the irrigation volume required to reach maximum retention increased, although no significant differences were recorded (Table 3).

Peat–coir blends. The initial sorptive behavior of peat at a 50% MC was affected by coir amendments. The wettability curves for peat and coir blends indicated few differences between HC 1 and HC 2 (Fig. 4). By substrate, the maximum VWC increased as the volume of coir in the blend increased ($P < 0.0001$). Peat blends with 45% coir had a greater maximum VWC than blends with 15% coir (61.0% compared with 55.3%, respectively). Neither blend was different from peat with 30% coir, with an average VWC of 57%. Coir-amended peat had a 21% to 29% improvement in VWC than peat alone in HC 2 (Table 4). However, increasing the coir in blends did not improve the irrigation volume required to reach maximum VWC. Irrigation water capture fell short of CC for all blends. Peat amended with 15% coir had a lower CC than blends with higher ratios of coir.

Table 3. The surface irrigation volume (mL) required to reach maximum water retention for three substrate components prepared at three moisture contents (MC) following two wetting and drying (hydration) cycles (HC 1 & HC 2).

	Substrate moisture content								
	Coir			Peat			Pine bark		
Hydration cycle[i]	33%	50%	67%	33%	50%	67%	33%	50%	67%
HC 1	680 cd[ii]	520 cd	360 cd	1,440 ab	1,540 a	340 cd	560 cd	420 cd	240 d
HC 2	780 b–d	640 cd	380 cd	540 cd	980 a–c	240 d	780 b–d	320 cd	300 cd

[i] For hydration cycle 1 (HC 1), surface irrigation was applied in ten 200-mL events to determine water retention. For HC 2, materials were received, hydrated, dried to a 25% moisture content, and then rehydrated to either 33%, 50%, or 67% before testing. Surface irrigation was applied in ten 200-mL events to determine water retention.

[ii] Statistics using Tukey's honestly significant difference with $\alpha = 0.05$ are given throughout the table. Means with the same letter are not statistically different.

Discussion

Although coir and pine bark are very different in texture and appearance, their hydration efficiency was similar. At all moisture levels, coir and bark were affected minimally by MC or initial HCs. Both materials were able to reach their maximum irrigation retention after approximately two to four irrigation events. Coir is known to be a very hydrophilic, granular, and spongelike material (Bartley et al. 2019). Pine bark is more platelike, and generally coarse to promote drainage and air-filled porosity (Drzal et al. 1999). Their texture was not only apparent from particle size analysis, but also in water retention. With 41.3% of coir

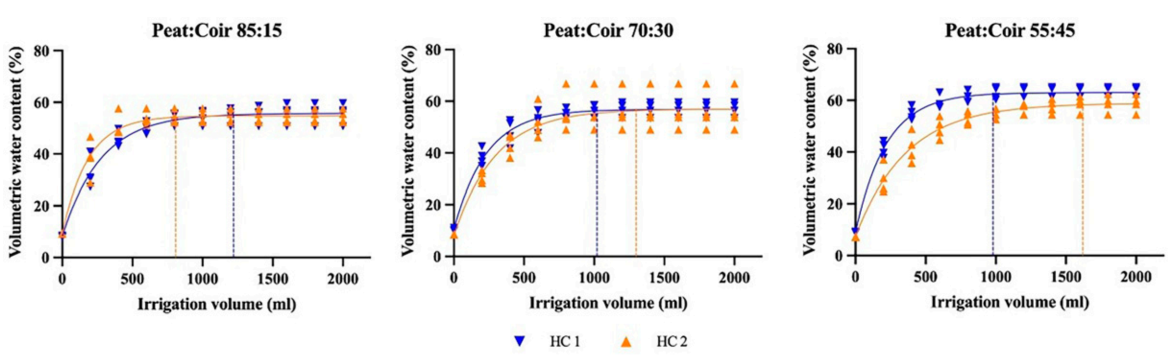

Fig. 4. The volumetric water content capture rates of three peat:coir blended substrates following an initial hydration cycle (HC 1) and a second hydration cycle (HC 2). Substrate blends consist of either 85:15, 70:30, or 55:45 peat:coir by volume and were tested at a moisture content of 50% (by weight). Data points were modeled to derive the intercept at which 99% of the maximum volumetric water content was achieved.

Table 4. The irrigation volume required to reach the maximum volumetric water content (VWC) and container capacity of three peat:coir blended substrates after two wetting and drying (hydration) cycles.

Substrate blend[i]	Hydration cycle[ii]	Irrigation volume (mL)[iii]	Volumetric water content[iv]	Container capacity
85:15	1	1,220 ab[v]	55.8 NS	62.9 c
	2	820 b	54.9	62.9 c
70:30	1	980 b	57.0	68.9 ab
	2	1,300 ab	57.0	66.8 b
55:45	1	1,640 a	63.0	70.5 a
	2	980 b	59.0	67.5 ab

[i] Substrate blends consist of either 85:15, 70:30, or 55:45 peat:coir by volume.

[ii] For hydration cycle 1 (HC 1), materials were received "as is" and hydrated to > 75% moisture content (MC; by weight) before drying down to 50%. For HC 2, materials were hydrated to > 75% MC (by weight), dried to a 25% MC, and rehydrated to a 50% MC.

[iii] Surface irrigation was applied in ten 200-mL events. The cumulative volume required to reach the maximum water retention of the substrate was determined.

[iv] The maximum percentage (by volume) of water retained by the substrate from overhead irrigation.

[v] Statistics using Tukey's honestly significant difference with $\alpha = 0.05$ are given within columns. Means with the same letter are not statistically different.

NS = not significant.

particles passing a 0.5-mm sieve, water retention was very high. Conversely, bark—with 66% of particles retained in a 2-mm sieve—had the lowest average CC. However, bark can be processed in a variety of ways to have comparable physical and hydraulic characteristics to coir and peat (Bilderback et al. 2005). The consistency in sorptive behavior in the pine bark evaluated in our study suggests that bark should be evaluated further to improve water use efficiency.

From the data in Fig. 3, it is apparent that peat is most vulnerable to changes in sorptive behavior as a result of wetting and drying cycles. It is well documented from other investigations that the hydrophobicity of peat intensifies as MC decreases (Fields et al. 2014; Michel et al. 2001; Schulker et al. 2020). However, even at greater MCs, peat was rarely able to reach CC from surface irrigation. The largest disparity in water capture occurred in peat at a 33% MC during HC 1, when there was a 32.6% volumetric difference in irrigation capture vs. CC. This disparity could be attributed to hysteresis and hydrophobicity affecting preferential flow. Surface irrigation has the potential of gravity to drive water through the substrate, which allows water to move through the macropores quickly and reduces the incidence of lateral dispersion. Coupled with decreasing imbibition, peat struggled to demonstrate favorable hydration efficiency.

Blending coir with peat improved substrate wettability substantially. Adding just 15% coir by volume allowed peat to maintain a VWC of ~55% through a wetting and drying cycle. With blends of 30% and 45% coir, it was difficult to determine whether the effects were a result of the hydrophilic nature or smaller particle size of the coir. Smaller volumes of coir blended with peat should be evaluated to determine the threshold of coir to improve wettability.

The statistical approach used to quantify substrate wettability was helpful in identifying objectively the intercept at which a substrate approached its maximum VWC from overhead irrigation. Although the intercept at 99% of the maximum VWC was used for this study, the derivative of the monomolecular exponential model can be adjusted easily should the user determine a different threshold more valuable. Analyzing the data in this manner also draws attention to the variability demonstrated in this wettability procedure. Schulker et al. (2020) also recorded greater variability from surface irrigation than subirrigation when evaluating substrate hydration efficiency.

Conclusion

Data from these experiments provide evidence that the MC and preconditioning of a substrate can lead to differences in initial water capture efficiency. This information can be critical to growers, growing media manufacturers, and researchers alike. The wettability of peat was most affected by MC and the initial wetting and drying cycles. Hydration efficiency was improved in peat by blending in as little as 15% coir by volume. Future investigations should target the changes in sorptive behavior through multiple wetting and drying cycles, such as those experienced during plant production, and pragmatic solutions to improve substrate water use efficiency, such as improving the physical properties of pine bark and blended substrates.

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