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# Comparison of Water Capture Efficiency through Two Irrigation Techniques of Three Common Greenhouse Soilless Substrate Components

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**Abstract:** Substrate wettability is an important factor in determining effective and efficient irrigation techniques for container-grown crops. Reduced substrate wettability can lead to lower substrate water capture, excessive leaching and poor plant growth. This research examined substrate water capture using surface and subirrigation under three initial moisture contents (IMC). Sphagnum peat moss, coconut coir, and pine bark were tested at IMCs of 67% 50%, and 33%. Substrate water capture was influenced by both IMC and irrigation technique. Surface irrigation increased the water capture of coir and peat, regardless of IMC, whereas IMC influenced pine bark water capture more than irrigation method. Surface-irrigated coir at or above 50% IMC provided the greatest water capture across all treatments. The first irrigation had the highest capture rate compared to all other events combined. Container capacities of pine bark and coir were unaffected by IMC and irrigation type, but the CC of peat was less by ~ 40% volumetrically under low IMC conditions. Coir, had the greatest ability to capture water, followed by pine bark and peat, respectively. Moisture content, irrigation type and component selection all influence the water capture efficiency of a container substrate.

**Keywords:** irrigation; soilless substrates; water; coconut coir; initial moisture; mass wetness; peatmoss; pine bark; wettability; capillary rise; container capacity; capture rate

## 1. Introduction

Water use efficiency of horticultural soilless substrates represents one of the biggest variables in container plant production. With nearly 21,500 acres of land devoted to greenhouse operations in the U.S., representing a 148% increase since 1998, growers specializing in container plant production need to be able to understand how irrigation specifics impact water use efficiency of soilless substrates [1]. Greenhouse production uses less water and fewer nutrients than many agricultural resources [2], and decrease crop water requirements by up to 40% compared to open field cultivation [3–5]. As water quality, conservation, scarcity and operational costs increase, plant producers must adopt new strategies to improve the sustainable use of water to confront water-climate policies [6–8]. In order for growers to meet these increasing regulations in water use, we need to increase the overall understanding of irrigation techniques.

Two parameters affecting water efficiency in substrates are container capacity (CC) [9–12] and wettability [13–17]. Both wettability and CC are vital to the wetting of a substrate, however neither completely describes the effectiveness of water capture during irrigation [18]. Container capacity is the maximum amount of water a substrate can hold after wetting and drainage. Wettability includes a liquid's ability to spread laterally at and below the surface of a material [19]. In substrates, proper wettability helps to provide a uniform distribution of water throughout the rooting environment [20]. Moisture content in substrates affects both wettability and CC of a substrate. Fields et al., [21] showed the variability in CC based on substrate and initial moisture content (IMC), with coir and pine bark being less variable than peat. Initial moisture content in this context references the moisture content prior to an irrigation event. At low moisture conditions, peat can have a ~30% lower CC than at high moisture conditions [11]. In mineral soils, hydrophobicity is caused by organic residues coating the mineral materials from the breakdown of organic matter. In substrates, most components are composed almost entirely of organic materials which complicates the nature of hydrophobicity. As organic materials naturally break down, the intensity of hydrophobicity can change, which then alters the substrate's behavior during rewetting [22,23]. Hydrophobicity issues also arise as organic materials dry, and materials such as peat and pine bark begin to see reductions in water capture based on repellency [13,24]. Adequate substrate particle structure, stability, density, and CC are needed to allow water movement through the containers [25,26].

Most irrigation is applied to the top of the soil column. However, in containers, the irrigation delivery direction can be reversed and delivered from the bottom (subirrigation). Irrigating from below can require a finer textured, micro-pore abundant substrate to take up water mainly through capillary action [27]. Conversely, greater air space (AS) and pore size diversity favor surface irrigation methods. Capillary action, the movement of water from a saturated zone upward into an unsaturated zone through surface tension and soil matric potential, provides water and nutrients to the plant root [28]. Subirrigation is a combination of flooding from a perched water table and capillary rise. Ebb and flow subirrigation, was found to reduce water use by ~40% compared to hand watering [29,30]. The confluence of these factors combine to play a pivotal role in the effectiveness of water uptake in specific combinations of irrigation method and substrate components. Water transport research in mineral soils [31] provides the basis to understand soilless substrate systems, but the substantial differences in physical properties and their accompanying calculated values between soil and soilless substrates requires substrate-specific research.

Research has identified the impacts hydrophobicity can have on the wettability of some horticultural substrates [13,19,20]. However, few have studied the influence of irrigation delivery method on the ability of substrates to capture water or rehydrate. In soilless substrates, water distribution in the container can largely change due to a substrate's hydrophobicity, physical characteristics (texture/particle size), as well as the irrigation method used. The objective of this study was to characterize the water capture and retention of three substrate components based on irrigation technique and IMC.

## 2. Materials and Methods

### 2.1. Preparation of Substrates

On 11 April, 2019, sphagnum peat (Premier Pro-Moss, Quakertown, PA) was hydrated and fluffed to an initial IMC of 70% (by weight; ~2.5 *w*). To do that, peat was removed from the compressed bale and placed into a large tub, water was then added in 3 L increments after which peat was mixed/agitated by hand to allow water absorption. Moisture levels were then tested using an Ohaus MB27 soil moisture determination balance (Ohaus Corp., Parsippany, NJ) to determine further water additions needed to bring peat to an initial moisture of 70%. On 15 April, 2019, three compressed bricks of coconut coir (Densu Coir, Ontario, Canada) were hydrated individually by adding 14 L of water (in 1 L increments), by hand, until the coir was completely broken apart. Moisture levels were then tested using the soil moisture balance to determine further water additions needed to bring coir to an initial moisture of 70%. On 16 April, 2019, 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 CC of 55% volumetric water content (VWC). The volume of pine bark was measured out, initial moisture level was tested and recorded before the bark was further hydrated to a moisture level of 70%.

Each substrate component was tested under three IMC treatments. The most common and recommended IMC for potting soils has a mass wetness of 1.0 g $g^{-1}$. To test effects of IMC, each component was also brought to half (0.5 g $g^{-1}$) and double (2.0 g $g^{-1}$) this normal level, which resulted in percent IMCs of 33%, 50%, and 67% by weight. To do this the wet weights and dry weights were determined by taking 500 g subsamples of each substrate, weighing, drying, and then reweighing. Substrate samples were wet to an initial IMC of 70% IM, before being air-dried down to initial IMC's of 67%, 50%, and 33% IMC. Initial IMC and total weight of each sample were used to calculate how much water needed to be lost to reach initial IMC's of 67% IM, 50% IM, and 33% IM. Using a 160 cm × 49 cm × 69 cm four-tier PVC-enclosed dehumidifying chamber, substrates were allowed to air dry to desired wetness. Once the target initial IMC was reached, samples were transferred to plastic bags and sealed to prevent further water loss, while allowing the substrate to reach moisture equilibrium.

### 2.2. Particle Size

Particle size distribution (Table 1) was performed on three 50 g oven dried samples of each substrate with 7 sieves. The sieve sizes used were 6.3 mm, 2.0 mm, 0.71 mm, 0.5 mm, 0.25 mm, 0.11 mm, and the bottom pan to collect fine particulates. The 7 sieves (6 sieves and the pan) were stacked together and substrate samples were poured into the top sieve, and placed into the RX-29 Ro-Tap sieve shaker (278 oscillations/min, 150 taps/min; W.S, Tyler, Mentor, OH). The sieves and pan were shaken for five min and the particle fractions retained on each sieve and the amount collected in the bottom pan (representing the smallest particle fractions) were weighed.

**Table 1.** Particle size distribution of three traditional greenhouse substrate components.

| | *Particle Size Distribution (%)* $^{z}$ | | |
|---|---|---|---|
| **Sieve (mm)** | **Coir** | **Peat** | **Pine Bark** |
| 6.3 | 0.2 | 2.0 | 8.6 |
| 2.0 | 6.0 | 17.0 | 45.0 |
| 0.71 | 40.2 | 29.0 | 30.6 |
| 0.5 | 19.8 | 11.2 | 7.2 |
| 0.25 | 26.0 | 25.0 | 5.8 |
| 0.11 | 5.4 | 11.4 | 1.8 |
| <0.11 (pan) | 2.4 | 4.4 | 1.0 |
| **Texture** | | | |
| Coarse $^{y}$ | 6.2 C c $^{v,u}$ | 19.0 B b | 53.6 A a |
| Medium $^{x}$ | 60.0 A a | 40.2 A b | 37.8 B b |
| Fines $^{w}$ | 33.8 B a | 40.8 A a | 8.6 C b |

$^{z}$ Particle size distribution calculated on a dry weight scale using means of three oven-dried samples. $^{y}$ Coarse = particles that are greater than 2.0 mm in diameter. $^{x}$ Medium = particles that are less than 2.0 mm but greater than 0.5 mm in diameter. $^{w}$ Fines = particles that measure less than 0.5 mm in diameter. $^{v}$ Values are means of percentages of the total sample. $^{u}$ 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.

### 2.3. Surface Irrigation

In order to determine the effects of IMC with surface applied irrigation, this experiment followed the procedures described by Fonteno et al. [18] and Fields et al. [20]. The equipment consisted of a transparent cylinder, 5 cm i.d. × 15 cm $h^{-1}$, with a mesh screen (mesh size 18 × 16; New York Wire, York, PA, USA) (Figure 1A), attached to one end, using rubber pressure plate rings (Soil moisture Equipment Corp., Santa Barbara, CA, USA); a 250-mL beaker; a 250-mL funnel; as well as a 10 mL plastic vial (4-cm diameter) with five evenly spaced 2.33 mm diameter holes in the base to act as a diffuser displayed in

Figure 1. This allowed the water dripping through the funnel to be evenly dispersed through the five holes onto the surface of the substrate in the cylinder.

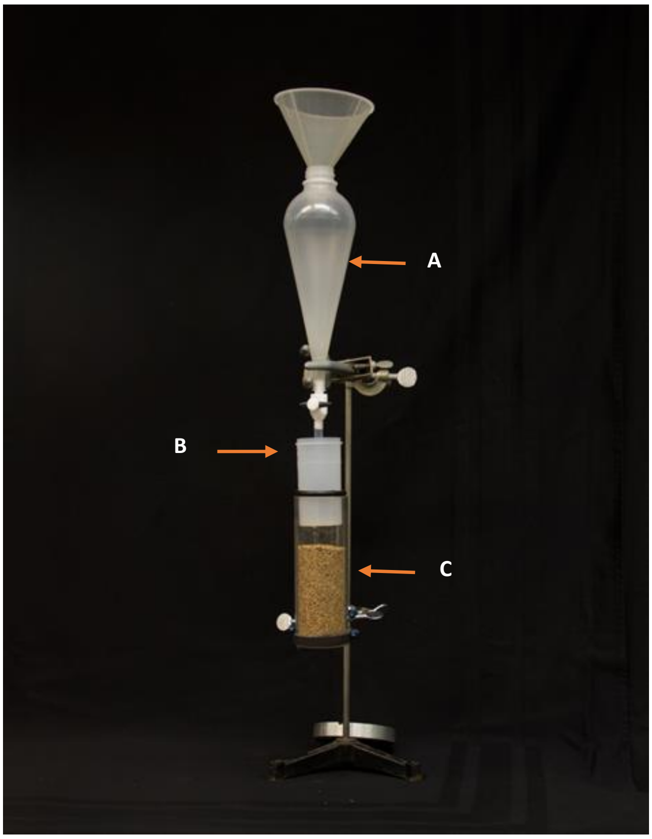


**Figure 1.** Surface irrigation apparatus. (**A**) Funnel, sparatory funnel with stopcock. (**B**) Water diffuser with O-ring above cylinder. (**C**) Sample cylinder with 200 mL of substrate.

The transparent cylinders were packed with each substrate component to have a weight within 5% of other samples of the same component. To achieve this, cylinders were filled (by weight) with substrate then raised 12 cm off a flat surface, then tapped four times to bring the top of all 4 replications to 10 cm from the base of the cylinder, representing 200 mL of substrate and providing similar Db across all replications. With three substrates, at three IMCs, and four replications there were a total of 36 experimental samples. After the cylinders were packed, each was fitted with a diffuser and placed in the clamps held up by a ring stand, just under the separatory funnel (Figure 1). Two hundred mls of water was poured into the separatory funnels and allowed to drip onto the surface of the substrate at an average rate of 40 mL min$^{-1}$, using the stopcock valve to control the flow. Water was applied in 10 individual hydration events. Substrates with an IMC of 33% required the rate of flow to be less to prevent ponding of water on the substrate surface which would have created a hydraulic head greater than 0.5 cm and alter the influence of any native hydrophobicity in the sample. Water was passed from the separatory funnel, through the diffuser, and onto the surface of the substrate. With the help of gravity, water was able to penetrate the surface of the substrate and percolate through the 10 cm depth. Some of the water volume was absorbed as it moved through the substrate, the rest was collected out of the bottom by a 250 mL beaker. After ~5 min, water flow ceased; the substrate was then held at equilibrium for two min. The effluent volume was measured and recorded while water retained was calculated by subtracting the amount of water applied (200 mL) from the amount of effluent captured. With the total event lasting ~7 min, 5 min time intervals were measured out in between events to keep treatments even. This procedure was repeated for each of the 10 hydration events.

*2.4. Subirrigation*

In order to understand how IMC influences substrate water capture through subirrigation, this experiment was conducted using materials and modified procedures described by Fonteno et al., [12]. The same transparent cylinders as described in surface irrigation above were prepared in the same way (Figure 2), The subirrigation method used an ebb and flood irrigation system (Hawthorn Hydroponics, Vancouver WA) 60.96 cm wide by 121.92 cm in length (Figure 2). Water was introduced into this system via a faucet and controlled through a series of gate valves connected to the system (Figure 3B). Water 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 bench, a standing copper pipe was cut to allow water to be held at 2.5 cm at a steady state (Figure 2C).

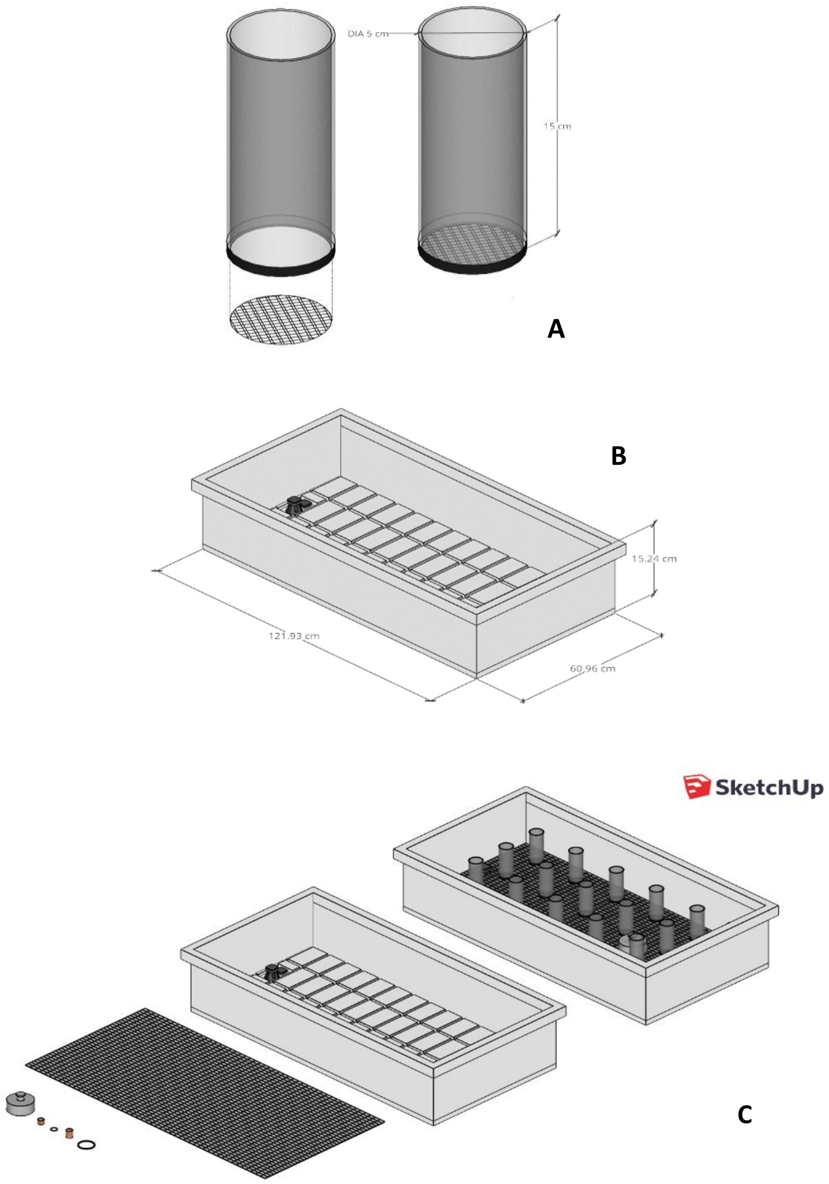


**Figure 2.** Subirrigation system. (Left, right, bottom) (**A**) Cylinder (15 cm × 5 cm) with rubber pressure plate ring at base with mesh screen with DIA representing the cylinder diameter. (**B**) Ebb and flood subirrigation system. (**C**) Separated full system (from left to right) with central weight, three copper leveling pipes, large steel ring (for raising wire screen off surface), black wire mesh screen, fully assembled system.


**Figure 3.** Ebb and flood subirrigation system. (**A**) Container capacity testing with 2 kg aluminum weights. (**B**) Partially constructed ebb and flood unit with aluminum rings with mesh screen. (**C**) Fully constructed system complete with packed substrate cylinders.

The transparent cylinders were packed in identical manner as the samples used in the surface irrigation system. Cylinders were then placed on an elevated mesh screen to optimize the lower surface area exposure to water. The unit was then filled with water. It took approximately one minute for the water to reach the bottom of the cylinders and another minute for the water to reach 2.5 cm above the base. At that time, water flow input equaled output, allowing constant flow of water without a change in water level. The substrate samples were kept in the unit for five minutes for each of the hydration events. Once an event was finished, water drained from the unit for one minute before each cylinder was weighed. The weights were used to calculate the amount of water captured by the substrate by subtracting it from the initial weight of the packed cylinders. This procedure was repeated 10 times (10 hydration events), with a total time of hydration equaling 50 min.

### *2.5. Container Capacity*

After the final hydration event was complete and final weights were taken, CC was then determined for each cylinder. The cylinders were returned to the ebb and flood unit (Figure 2), and CC was determined using a modified version of the NC State University Porometer Method [32]. After placed in the subirrigation unit, an aluminum weight of approximately 2 kg was placed on the top of each cylinder to prevent tipping and buoyancy (Figure 3A). The samples were then saturated from below by allowing water to flow into the unit until it reached 1/3 of the height of the sample (three cm from the base of the sample). After two minutes, additional water was allowed to enter the unit until reaching 2/3 of the height of the cylinder, or six cm from the base of the cylinder. After an additional two minutes, the water was applied until reaching the top of the sample within the cylinder (Figure 3A), 10 cm from the base of the cylinder. After saturating in the system for an additional 30 min, the water was drained and samples were reweighed to record changes in weight (water captured and retained). Samples were then placed into a forced-air drying oven at 105 °C for 48 h to dry, after which each sample was weighed and the dry weights were used to determine total water retained and IMC.

### 2.6. Water Capture Rate

Water CR was calculated for subirrigated substrates using a modified version of the flow rate formula to account for variables in this experiment, the equation was written as:

$$CR = \frac{C_i - C_p}{t} \tag{1}$$

where CR is the mL/min of water captured by the substrate after one irrigation event, $C_i$ [water capture (g) in the initial irrigation event] is the weight of the substrate after the present irrigation event (minus the weight of the cylinder), $C_p$ (previous water capture in grams) is the weight of the substrate (minus the cylinder) taken after the previous irrigation (for the first irrigation event, $C_p$ is equal to the pack weight of the cylinder (minus the weight of the cylinder), t is the amount of time per irrigation (in minutes). For surface irrigated samples that have a defined volume of water passing through the substrate, the equation was written as

$$CR = \frac{A_w - E}{t} \tag{2}$$

where CR is the amount of water captured by the substrate after one irrigation per unit time (in mL $min^{-1}$), $A_w$ is the amount of water applied to the substrate per irrigation event (in this case, 200 mL), E is the effluent captured after the individual irrigation event (in mL), t is the amount of time per irrigation event (minutes).

### 2.7. Water Capture Curves

The IMCs of 33%, 50%, and 67% were all determined by weight. Wettability curves were determined by VWC to describe the amount of water contained within the substrate. These curves show a VWC reading at event zero, and represent the percent VWC at the IMC. Therefore, an IMC of 50% (by weight) was actually 12% to 15% $v\,v^{-1}$ (moisture) for peat. For coir, an IMC of 50% ranged from 9% to 11% $v\,v^{-1}$, and for pine bark (at 50% IMC) they were 16% to 18% $v\,v^{-1}$.

### 2.8. Capture Efficiency Values

In order to provide both statistical and numeric comparisons, water capture efficiency of the substrates was described in three ways: (1) first hydration, (2) final hydration and (3) CC. First hydration was the amount of water absorbed by the substrate after one irrigation event, and compared across all substrates and moisture levels. Final hydration was the amount of water absorbed by the substrate after the tenth irrigation event. Container capacity was the maximum water content the sample could hold after saturation and drainage. Physical properties of the substrates, including CC, AS, total porosity (TP), and bulk density (Db) were derived using the NC State University Porometer method [20] with three representative samples of each substrate, and CC is reported in Table 2.

**Table 2.** First hydration ($H_1$), container capacity (CC), and final hydration ($H_{10}$) of three substrate components analyzed at three different initial moisture contents (IMC) irrigated by either subirrigation or surface application.

| | ***Coir*** | | | | ***Peat*** | | | | ***Pine Bark*** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Surface* | $H_1$ $^{z}$ | $H_{10}$ $^{y}$ | CC$^{x}$ | S $^{*w}$ | $H_1$ | $H_{10}$ | CC | S * | $H_1$ | $H_{10}$ | CC | S * |
| 33% IMC | 35.4 de | 59.6 b | 75.4 ab | L ** Q * | 17.8 cd | 37.6 c | 78.3 ab | L ** Q * | 24.1 c | 42.1 bc | 54.5 a | L * Q * |
| 50% IMC | 67.6 b $^{v}$ | 73.5 a | 73.5 b | L * Q * | 21.1 c $^{v}$ | 37.1 c | 73.1 b | L ** Q * | 45.2 b | 50.2 ab | 59.6 a | L * Q * |
| 67% IMC | 75.2 a | 75.2 a | 76.0 ab | NS | 67.6 a | 70.8 a | 81.8 a | NS | 51.9 a | 57.9 a | 57.1 a | L * Q * |
| *Subirrigation* | | | | | | | | | | | | |
| 33% IMC | 32.2 e | 47.7 c | 76.1 ab | L ** Q * | 8.6 d | 15.7 d | 49.3 d | L ** Q * | 28.1 c | 36.6 c | 56.2 a | L *** Q * |
| 50% IMC | 40.0 d | 51.6 bc | 74.7 b | L * Q * | 15.7 cd | 26.0 d | 58.0 c | L * Q * | 40.9 b | 42.5 bc | 60.5 a | L * Q * |
| 67% IMC | 48.7 c | 54.7 bc | 79.0 a | L * Q * | 45.6 b | 53.5 b | 77.3 ab | L * Q * | 46.5 ab | 48.5 b | 57.3 a | L * Q * |
| *Significance* $^{v}$ | L * Q * | L * Q * | L * Q * | | L * Q * | L * Q * | L * Q * | | L* Q* | L * Q * | NS | |

$^{z}$ $H_1$ = the amount (by volume) of water that is absorbed by the substrate after one irrigation event. $^{y}$ $H_{10}$ = the amount (by volume) of water that is absorbed by the substrate after the final hydration event. $^{x}$ CC = maximum volumetric moisture content attained by sample. $^{w}$ Significance: Linear (L) and Quadratic (Q) regression significance test, NS = nonsignificant, *** $p \leq 0.001$, ** $p \leq 0.01$ * $p \leq 0.05$ down all columns for peat, coir, and pine bark. S *: Linear (L) and Quadratic (Q) regression significance test, NS = nonsignificant, *** $p \leq 0.001$, ** $p \leq 0.01$ * $p \leq 0.05$ across rows for individual substrates, moisture contents, and irrigation techniques. $^{v}$ Statistics using Tukey's honestly significant difference with alpha = 0.05 are given down individual columns at a given initial moisture content. Means with the same letter are not statistically different.

Statistics were determined using SAS v. 9.4 (SAS Institute; Cary, NC, USA). A Tukey's HSD test with alpha = 0.05 was used to identify differences and similarities between substrates at individual IMCs and irrigation events. This test also determined the similarities and differences of CC, first hydration, and final hydration across substrates, IMCs, and irrigation techniques. Both linear and quadratic regression was performed and significance was determined using $p$ values with significance ranging from > 0.001 to 0.05. An analysis of variance test was conducted to test the effects of initial IMC and irrigation technique on CC, first hydration and final hydration within individual substrate components.

## 3. Results

### 3.1. Particle Size

Substrate particle size analysis was performed on all three substrates, with the results displayed in Table 1. Coir represented the substrate with the highest percentage of particles smaller than 2.0 mm, representing 93.8% of all particles tested while pine bark showed the highest percentage of coarse particles with a value of 53.6%. Peat occupied a middle ground between coir and pine bark with 13% more coarse particles than coir, but still 34% less than that of pine bark.

### 3.2. Coir Water Capture

The VWC curves for coir (Figure 4A–C) indicated a pattern directly related to IMC. Regardless of IMC, the first hydration event had the most water absorbed by the substrate compared to all other irrigation events. The IMC affected the amount of water absorbed in the first hydration, and increased as the IMC increased. For surface irrigation, coir at 33% IMC (Figure 4A) needed four irrigation events to reach maximum absorption through irrigation. Coir at 50% IMC (Figure 4B) needed two events to reach maximum absorption and at 67% IMC (Figure 4C) needed just one. For subirrigation, IMC contributed to the ability of coir to absorb water across all 10 events, however, coir never reached a steady state or maximum absorption at any initial moisture level with subirrigation. At 50% IMC, coir reached a final hydration of 73.5% VWC through surface irrigation and 51.6% VWC with subirrigation (Table 2). However, at 33% IMC, coir was ~20% VWC below the CC after the final hydration in both irrigation techniques. Coir samples at 67% IMC reached near CC in one irrigation using the surface application technique, with a final hydration value < 1% below the CC.

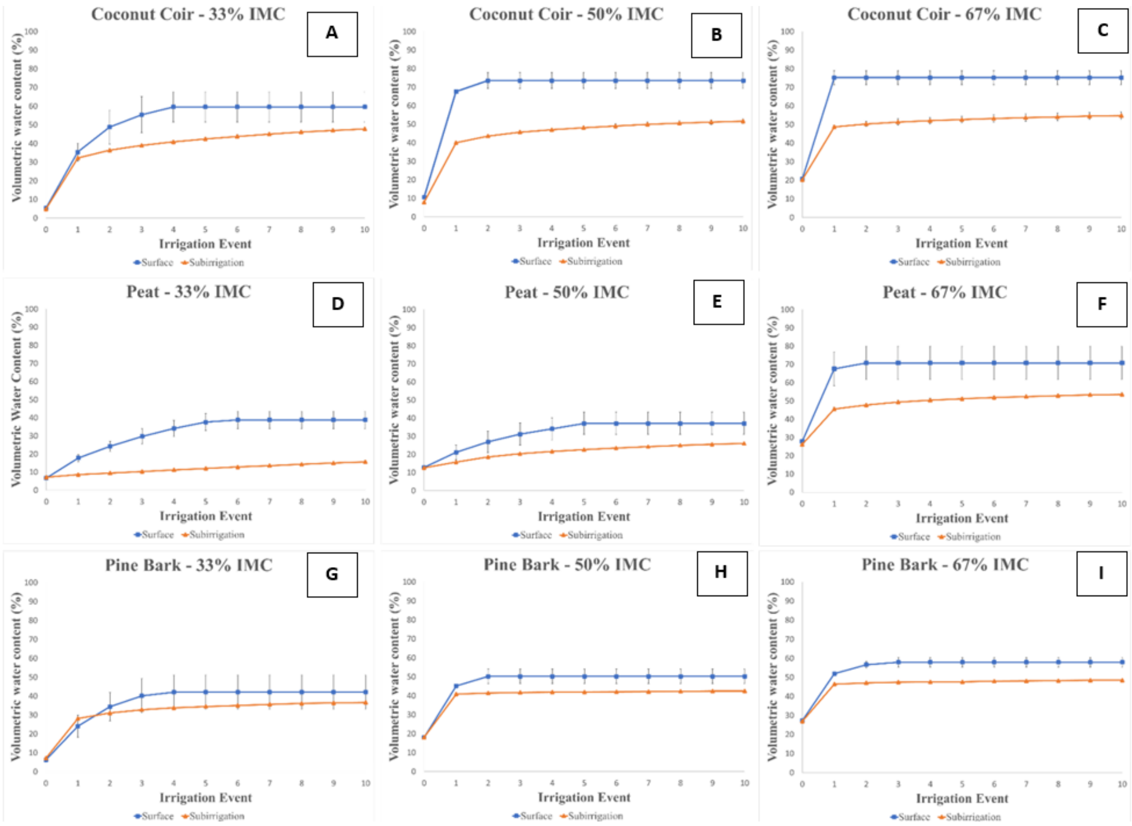


**Figure 4.** Substrate water capture volumetric water content curves for peat, coir, and pine bark over ten irrigation events at three moisture contents and two irrigation techniques. With (**A**) coir at 33% IMC, (**B**) coir at 50% IMC, (**C**) coir at 67% IMC, (**D**) representing peat at 33% IMC, (**E**) peat at 50% IMC, (**F**) peat at 67% IMC, (**G**) pine bark at 33% IMC, (**H**) pine bark at 50% IMC, and (**I**) pine bark at 67% IMC.

The capture rate of coir was affected by irrigation method. Capture rates for coir were greatest at 50% IMC (Figure 5), where 50% IMC captured ~60% VWC of water through one irrigation event whereas 67% IMC captured ~50% VWC of water in surface irrigation. However, with subirrigation the differences were smaller. Initial moisture contents of 33%, 50%, and 67% were within 8% of total water captured (volumetrically) between each increase in moisture. Also, as IMC increased, the difference between events one and 10 were smaller. With surface irrigation, as IMC increased, fewer events were needed to reach maximum capture. In subirrigation, the effect was similar, although 33% IMC and 50% IMC showed minimal differences in water capture.

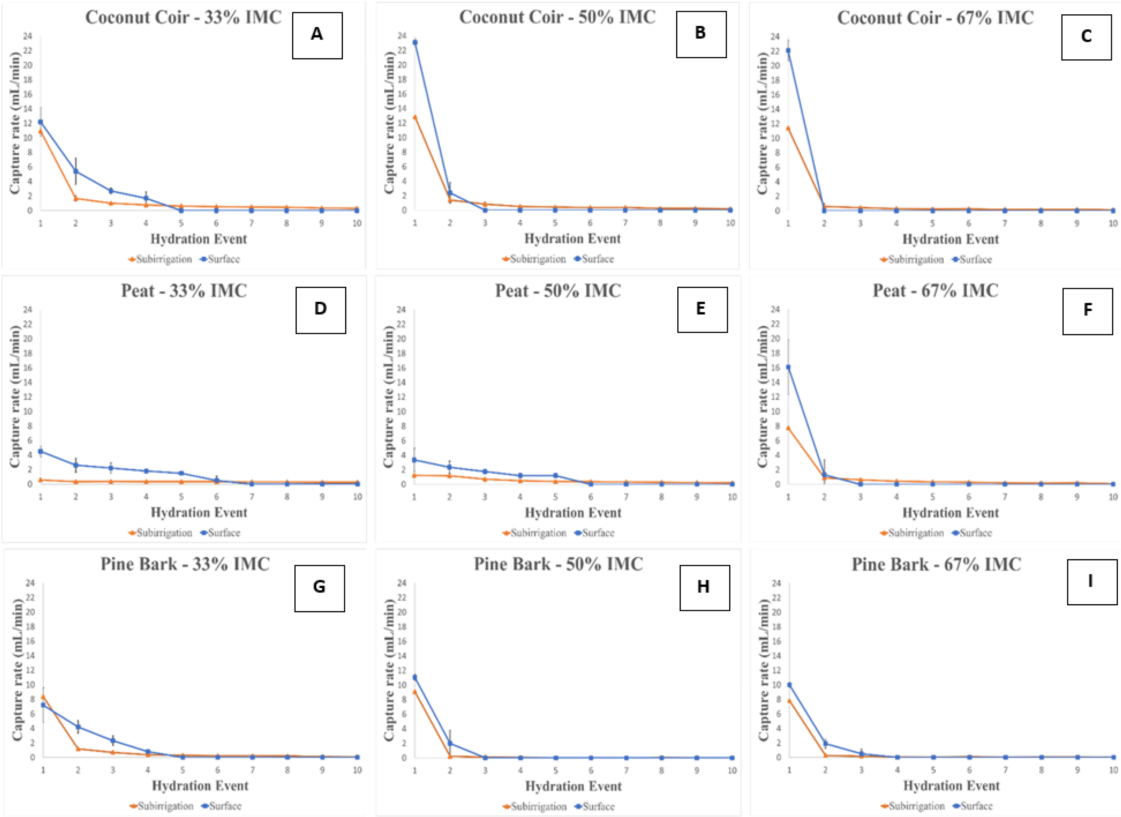


**Figure 5.** Water capture rate (CR) for peat, coir, and pine bark over ten irrigation events at three moisture contents and two irrigation techniques. With (**A**) coir at 33% IMC, (**B**) coir at 50% IMC, (**C**) coir at 67% IMC, (**D**) representing peat at 33% IMC, (**E**) peat at 50% IMC, (**F**) peat at 67% IMC, (**G**) pine bark at 33% IMC, (**H**) pine bark at 50% IMC, and (**I**) pine bark at 67% IMC.

### *3.3. Peat Water Capture*

The VWC curves (Figure 4D–F) for peat, similar to coir, identified a pattern related to IMC. With surface irrigation, 33% IMC required six irrigation events to reach maximum absorption through irrigation while 50% IMC needed just five irrigation events (Figure 4D,E), showing very little difference between the two IMC levels. At 67% IMC, maximum absorption was reached in two surface irrigation events. Comparing the surface and subirrigated VWC curves (Figure 4D–F), there was ~20% less water taken up by capillary rise than from gravitational flow. Peat contained 81% of particles < 2 mm (coir had 92%) and nearly 17% of particles between 6.3 mm and 2 mm (Table 1). At both 50% IMC and 33% IMC, the final hydration values were less than 20% VWC, with subirrigated peat at 33% IMC reaching less than 20% VWC after 10 irrigations (Table 2). At 67% IMC, the first hydration of subirrigated peat increased by 30% VWC compared to that of 50% IMC.

The water capture of peat was affected by both irrigation method and IMC. Water CRs for peat show the effects of a low moisture condition on hydration with surface irrigation at 33% IMC reaching ~5 mL $min^{-1}$ and 50% IMC reaching ~4 mL $min^{-1}$ (Figure 5E). Subirrigated peat at 33% IMC and 50% IMC had much lower CRs than surface irrigation, with CRs at or below 1 mL $min^{-1}$. Peat did not begin to show a change in hydration until IMCs of 67% in both irrigation methods, with very minimal differences between 33% IMC and 50% IMC. Surface CR at 67% IMC, while more variable than subirrigation, reached 16 mL/min while subirrigation peaked ~8 mL $min^{-1}$ (Figure 5). The strong interaction between water capture and IMC was clearly evident in peat.

### 3.4. Pine Bark Water Capture

Pine bark had a more consistent increase in VWC over the 10 irrigation events than either peat or coir. Of the three substrates, bark contained the highest percentage of coarse particles (Table 1), while also having a similar portion of medium (2.0–6.3 mm) sized particles compared to peat. The VWC curves (Figure 4G-I) identify a degree of consistency between irrigation techniques, regardless of initial moisture level or irrigation method. At 50% IMC and 67% IMC, subirrigation produced maximum irrigation absorption after one irrigation event, with less than 2% difference between first and final hydration. At all IMCs, surface irrigation had higher VWC after the final irrigation event compared to subirrigation, but the difference between surface irrigation and subirrigation after the final hydration was less than 10% VWC (Table 2). Similar to coir, pine bark achieved maximum capture within the first two to three irrigations at 50% IMC and 67% IMC in both irrigation methods. At 50% IMC, the difference in first hydration between surface and subirrigation was < 5% VWC. Similar to coir, the CC was not influenced by IMC or irrigation method. For bark, water capture differences are evident between 33% and 50% IMC. First hydrations increased from ~25% VWC to ~42% VWC (Figure 4G–I). Unlike coir and peat, pine bark showed less variability by irrigation method, with all first and final hydrations between 50% IMC and 67% IMC less than 8% VWC gain between all ten irrigation events. Pine bark water capture was the most consistent of the three substrate materials.

Water CRs also showed similarities across irrigation methods, with subirrigation having the higher CR at 33% IMC (Figure 5G). In just one hydration event, pine bark at 67% IMC reached 0.90 (90%) of its CC by surface irrigation and 0.81 (81%) of its CC by subirrigation. Water CRs for pine bark at 50% IMC and 67% IMC are within 2 mL/min of each other at the first hydration, with surface irrigation representing the maximum CR across all pine bark treatments. The low variability in water capture and high percentage of coarse and medium sized particles (Table 1) allowed pine bark to have a high capture efficiency, regardless of irrigation technique.

### 3.5. Capture Rate

Capture rates of surface-irrigated samples were highest in coir, regardless of IMC. At 50% IMC, coir CR was ~23 mL min$^{-1}$ before falling to ~3 mL/min by the second irrigation event (Figure 5E). The steep drop in CR was attributed to the substrate's ability to absorb water at such a high rate during the first irrigation, nearly reaching the maximum it could absorb (through surface application) after one irrigation event. With first hydrations capturing 67.6% VWC for 50% IMC and 75.2% VWC for 67% IMC, coir had the highest absorption rate of all three substrates. The lower initial moisture conditions in peat at 33% IMC and 50% IMC impacted CR more so than irrigation method (Figure 5A,B), further reducing the wettability of low-moisture peat. Conversely, the similar responses of pine bark between IMC and irrigation method could be attributed to increasing particle size which might have decreased variability in uptake. The water volumes absorbed by pine bark were less than coir, however the CC of pine bark was ~20% lower volumetrically than that of coir, giving pine bark physically less capacity to hold water.

## 4. Discussion

From the data in Figures 4 and 5, it appears that initial moisture content prior to the first irrigation event had the overall greatest effect on the water capture and retention of peat, coir, and pine bark across both irrigation techniques. The container capacity of pine bark and coir were less affected by irrigation technique than peat. Surface irrigation provided the highest water capture in the first hydration across nearly all substrates and IMCs. Peat had higher initial and final hydration values with surface irrigation compared to subirrigation over all IMCs.

At all initial moisture levels, coir was able to take up water. However, IMC altered the intensity of imbibition. With surface irrigation, coir at 33% IMC needed four irrigation events to reach its maximum of 60% VWC. At 50% IMC, coir needed two irrigation events, and at 67% IMC it needed just one for water capture to equal CC. Coir is known to be very hydrophilic, having a sponge-like ability to capture and hold water [33]. Surface irrigation has the additional potential of gravity to draw water through the substrate, allowing droplets to travel a path of least resistance. This allows water to move through macro and mesopores to hydrate the substrate. Conversely, with subirrigation, water must travel via capillary action and against gravity, along particle surfaces and through mostly micro-pores [34]. Initial moisture content did not have an effect on coir CC. With 92% of coir particles ranging from 2 mm or less (Table 1), water retention was very high.

For peat, IMC had the greatest influence on the substrate's ability to capture water with surface irrigation. As is well documented, intensity of hydrophobicity of peat increases at lower substrate moisture contents. These hydrophobic intensities can influence rewetting and impair the physical properties of the substrate [35,36]. At 33% IMC and 50% IMC, peat had difficulty hydrating through the first five irrigation events (Figure 4A). In the case of peat at 33% IMC and irrigated from the surface, water delivery from the separatory funnel had to be slowed to reduce ponding of water on the surface and increasing the hydraulic head at the substrate surface. For perspective, the first hydration at 33% IMC and 50% IMC through surface irrigation for peat was 17.8% and 21.1% (Table 2) respectively, while the first hydration of coir at the same moisture levels reached 35.4% and 67.6% respectively (Table 2). It wasn't until 67% IMC that peat began to capture and retain water during surface irrigation. The large proportion of coarse particles may relate to a greater portion of macro-pores in peat than coir (Table 1). These larger pores allowed surface irrigated water to preferentially flow through peat, even at lower initial moisture levels. Water moved through the large pores with less wetting of the substrate matrix due to increased intensity of hydrophobicity of the peat at both 33% IMC and 50% IMC Conversely, with subirrigation, at 33% IMC, peat was unable to eclipse 13% VWC after 10 irrigation events, representing the lowest first hydration of all treatments. At 50% IMC, peat reached 23% VWC with a final hydration of 37.1% VWC and a CC of 58.0 (Table 2). Compared to coir, irrigation method and IMC both impacted the CC of peat. However, at 67% IMC, the substrate absorbed water in the first irrigation event. The capture potential, or total volumetric water captured, of peat was nearly 40% less than that of coir.

In pine bark, an increase in fine (greater than 0.5 mm) particles has been shown to greatly influence the physical properties (AS and CC), while larger particle sizes had a minor influence on physical properties [9]. Larger particles, for surface irrigation, may provide water with more channels to move through the container, better hydrating the bark as pine bark just doesn't have as much surface area/microporosity for absorption. However, micro and meso-pores have higher abilities to capture and retain water. Larger pore sizes tend to drain more easily under gravitational potentials than smaller pores [37]. Pine bark can have variable properties based on processing, and it can have more AS, lower TP and easily available water than both peat and coir [38]. Pine bark had the most similar water capture and retention across all IMC and, aside from 33% IMC, reached their maximum VWC in the first two irrigation events.

## 5. Conclusions

Comparing first hydration, final hydration, and capture rate across all treatments (Table 2), there were varied effects among irrigation methods and IMCs. Peat was highly affected by IMC, the intensity of hydrophobicity was altered by IMC, and irrigation delivery. Coir and peat, through every IMC, captured less water through subirrigation than surface irrigation. Most notably, the higher the initial moisture content in the substrate prior to irrigation, the greater the overall water capture. These three substrate components demonstrated markedly different responses to water capture and retention in response to irrigation method and IMC.

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## References

1. U.S. Department of Agriculture. *Census of Horticultural Specialties*; U.S. Department of Agriculture: Washington, DC, USA, 2014.
2. Stanghellini, C. Horticultural production in greenhouses: Efficient use of water. *Acta Hortic.* **2014**, *1034*, 25–32. [CrossRef]
3. Fernandes, C.; Corá, J.; Araújo, J. Reference evapotranspiration estimation inside greenhouses. *Sci. Agric.* **2003**, *60*, 591–594. [CrossRef]
4. Kitta, E.; Bartzanas, T.; Katsoulas, N.; Kittas, C. Benchmark irrigated under cover agriculture crops. *Agric. Agric. Sci. Procedia* **2015**, *4*, 348–355. [CrossRef]
5. Levidow, L.; Zaccaria, D.; Maia, R.; Vivas, E.; Todorovic, M.; Scardigno, A. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. *Agric. Water Manag.* **2014**, *146*, 84–94. [CrossRef]
6. Daccache, A.; Ciurana, J.S.; Rodriguez Diaz, J.A.; Knox, J.W. Water and energy footprint of irrigated agriculture in the Mediterranean region. *Environ. Res. Lett.* **2014**, *9*, 1–12. [CrossRef]
7. Egea, G.; Fernández, J.E.; Alcon, F. Financial assessment of adopting irrigation technology for plant-based regulated deficit irrigation scheduling in super high-density olive orchards. *Agric. Water Manag.* **2017**, *187*, 47–56. [CrossRef]
8. Montesano, F.F.; Van Iersel, M.W.; Boari, F.; Cantore, V.; D'Amato, G.; Parente, A. Sensor-based irrigation management of soilless basil using a new smart irrigation system: Effects of set-point on plant physiological responses and crop performance. *Agric. Water Manag.* **2018**, *203*, 20–29. [CrossRef]
9. Handreck, K.A.; Black, N.D. *Growing Media for Ornamental Plants and Turf*; New South Wales University Press: Kensington, Australia, 1984; pp. 115–117.
10. Puustjarvi, V. Physical properties of peat used in horticulture. *Acta Hortic.* **1974**, *37*, 1922–1929. [CrossRef]
11. Milks, R.R.; Fonteno, W.C.; Larson, R.A. Hydrology of horticultural substrates: II. Predicting physical properties of media in containers. *J. Am. Soc. Hortic. Sci.* **1989**, *114*, 53–56.
12. Wallach, R.; da Silva, F.F.; Chen, Y. Hydraulic characteristics of Tuff (Scoria) used as a container medium. *J. Am. Soc. Hortic. Sci.* **1992**, *117*, 415–421. [CrossRef]
13. Michel, J.C.; Riviere, L.M.; Bellon-Fontaine, M.N. Measurement of wettability of organic materials in relation to water content by the capillary rise method. *Eur. J. Soil Sci.* **2001**, *52*, 459–467. [CrossRef]
14. Urrestarazu, M.; Guillen, C.; Carolina Mazuela, P.; Carrasco, G. Wetting agent effect on physical properties of new and reused rockwool and coconut coir waste. *Sci. Hortic.* **2008**, *116*, 104–108. [CrossRef]
15. Levesque, M.P.; Dinel, H. Fiber content, particle-size distribution and some related properties of four peat materials in Eastern Canada. *Can. J. Soil Sci.* **1977**, *57*, 187–195. [CrossRef]
16. Bunt, A.C. *Media and Mixes for Container-Grown Plants*, 2nd ed.; Unwin Hyman Ltd.: London, UK, 1988.
17. Bilderback, T.E.; Lorscheider, M.R. Wetting agents used in container substrates are they BMP's? *Acta Hortic.* **1997**, *450*, 313–319. [CrossRef]
18. Fonteno, W.C.; Fields, J.S.; Jackson, B.E. A pragmatic approach to wettability and hydration of horticultural substrates. *Acta Hortic.* **2013**, *1013*, 139–146. [CrossRef]
19. Letey, J.; Osborn, J.; Pelishek, R.E. Measurement of liquid-solid contact angles in soil and sands. *Soil Sci.* **1962**, *93*, 149–153. [CrossRef]
20. Fields, J.S.; Fonteno, W.C.; Jackson, B.E. Hydration efficiency of traditional and alternative greenhouse substrate components. *HortScience* **2014**, *49*, 336–342. [CrossRef]
21. Fields, J.S.; Fonteno, W.C.; Jackson, B.E.; Heitman, J.L.; Owen, J.S., Jr. Hydrological properties, moisture retention, and draining profiles of wood and traditional components for greenhouse substrates. *HortScience* **2014**, *49*, 827–832. [CrossRef]
22. Jouany, C.; Chenu, C.; Chassin, P. Wettability of soil constituents from angle measurements: Bibliographical review. *Sci. Sol.* **1992**, *30*, 33–47.
23. Dekker, L.W.; Ritsema, C.J. Wetting patterns and moisture variability in water repellent Dutch soils. *J. Hydrol.* **2000**, *232*, 148–164. [CrossRef]

24. Beardsell, D.V.; Nichols, D.G. Wetting properties of dried-out nursery container media. *Sci. Hortic.* **1982**, *17*, 49–59. [CrossRef]
25. Elia, A.; Parente, A.; Serio, F.; Santamaria, P. Some aspects of trough benches system and its performances in cherry tomato production. *Acta Hortic.* **2003**, *614*, 161–166. [CrossRef]
26. Oh, M.M.; Cho, Y.Y.; Kim, K.S.; Son, J.E. Comparisons of water content of growing media and growth of potted kalanchoe among nutrient-flow wick culture and other irrigation systems. *HortTechnology* **2007**, *17*, 62–66. [CrossRef]
27. Biernbaum, J.A. Subirrigation could make environmental and economical sense for your greenhouse. *Prof. Plant Grow. Assn. Nwsl.* **1993**, *24*, 2–14.
28. Uva, W.L.; Weiler, T.C. Economic analysis of adopting zero runoff subirrigation systems in greenhouse operations in the northeast and north central United States. *HortScience* **2001**, *36*, 167–173. [CrossRef]
29. Holcomb, E.J.; Gamez, S.; Beattie, D.; Elliott, G.C. Efficiency of fertigation programs for baltic ivy and asiatic lily. *Hort. Technol.* **1992**, *2*, 43–46. [CrossRef]
30. Dumroese, R.K.; Pinto, J.R.; Jacobs, D.F.; Davis, A.S.; Horiuchi, B. Subirrigation reduces water use, nitrogen loss, and moss growth in a container nursery. *Nativ. Plants J.* **2006**, *7*, 253. [CrossRef]
31. Russo, D.D.G. *Water Flow and Solute Transport in Soils: Developments and Applications*; Springer: Berlin/Heidelberg, Germany; New York, NY, USA, 1993.
32. Fonteno, W.C.; Hardin, C.T.; Brewster, J.P. *Procedures for Determining Physical Properties of Horticultural Substrates Using the NCSU Porometer. Horticultural Substrates Laboratory*; North Carolina State University: Raleigh, NC, USA, 1995.
33. Abad, M.; Frones, F.; Carrion, C.; Noguero, V. Physical properties of various coconut coir dusts compared to peat. *HortScience* **2005**, *40*, 2138–2144. [CrossRef]
34. Biernbaum, J.A.; Versluys, N.B. Water Management. *HortTechnology* **1998**, *8*, 504–509. [CrossRef]
35. Valat, B.; Jouany, C.; Riviere, L.M. Characterization of the wetting properties of air dried peats and composts. *Soil Sci.* **1991**, *152*, 100–107. [CrossRef]
36. Michel, J.C. Study of the Wettability of Organic Materials Used as a Culture Support. Ph.D. Thesis, Agrocampus Ouest, Rennes, France, 1998.
37. Drzal, M.S.; Fonteno, W.C.; Cassel, D.K. Pore fraction analysis: A new tool for substrate testing. *Acta Hortic.* **1999**, *481*, 43–54. [CrossRef]
38. Bilderback, T.E.; Warren, S.L.; Owen, J.S.; Albano, J.P. Healthy substrates need physicals too! *HortTechnology* **2005**, *15*, 747–751. [CrossRef]


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