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The Use of Dewpoint Hygrometry to Measure Low Water Potentials in Soilless Substrate Components and Composites

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Abstract: Plant water availability in soilless substrates is an important management consideration to maximize water efficiency for containerized crops. Changes in the characteristics (i.e., shrink) of these substrates at low water potential (<−1.0 MPa) when using a conventional pressure plate-base can reduce hydraulic connectivity between the plate and the substrate sample resulting in inaccurate measures of water retention. Soilless substrate components *Sphagnum* peatmoss, coconut coir, aged pine bark, shredded pine wood, pine wood chips, and two substrate composites were tested to determine the range of volumetric water content (VWC) of surface-bound water at water potentials between −1.0 to −2.0 MPa. Substrate water potentials were measured utilizing dewpoint hygrometry. The VWC for all components or composites was between 5% and 14%. These results were considerably lower compared to previous research (25% to 35% VWC) utilizing conventional pressure plate extraction techniques. This suggests that pressure plate measurements may overestimate this surface-bound water which is generally considered unavailable for plant uptake. This would result in underestimating available water by as much as 50%.

Keywords: available water; coconut coir; dewpoint potentiometer; peat; pine bark; pine tree substrate; substrate processing; surface-bound water; unavailable water; wood substrate

1. Introduction

Traditionally, substrate scientists separate the water storage capacity of a soilless substrate into two categories, available water (AW; water that is available for plant uptake) and unavailable water (water that is bound tightly to soil surfaces and is unavailable for plant uptake). Soil and substrate scientists separate the availability of water as a function of water potential, as water within the substrate matrix is held at various tensions by a combination of matric and gravitational potentials. To absorb water from the substrate matrix, plants exert suction which must overcome the water tension. As the substrate volumetric water content (VWC) and water potential decreases (tension increases) the water becomes less available for plant uptake. The water potential at which the substrate transitions from AW to unavailable is not exact, but instead plant water availability is gradually reduced as the substrate dries and substrate water potential becomes more negative [1]. Water that is less available for plant uptake is most often tightly bound to particle surfaces, known herein as surface-bound water (SBW).

Water typically becomes less available for common agricultural crops in soil at potentials between −1.0 and −2.0 MPa [2]. Often, soils and substrate researchers use a water potential of −1.5 MPa as the potential at which water becomes plant unavailable for calculation. It is understood that many plant species can survive in soils with water potentials well below −1.5 MPa. However, the change in actual water content as water potential becomes more negative with drying beyond −1.5 MPa is typically negligible, with miniscule losses in water content accounting for substantial drops in water potential thereafter. Denmead and Shaw [3] reported that plants started to reduce transpiration levels at water potentials as high as −0.2 MPa, and Caron et al. [4] indicated that horticultural crops grown in containerized peat-based soilless substrates begin to show stress signals at substrate water potentials as high as −0.003 MPa. However, utilizing substrate VWC at substrate water potentials of −1.5 MPa as an estimated transition value, scientists can estimate substrate AW as a proxy for substrate water storage capacity, the water held at water potentials between container capacity (CC; the maximum volume occupied by water in a soilless substrate after drainage) and the water held at substrate water potentials of −1.5 MPa [5]. This calculation is useful for practical management considerations and to compare substrates.

To determine relationships between soil (or substrate) water potential and VWC, Bouyoucos [6] described an apparatus that introduces suction upon soil samples. This idea was refined by Richards and Fireman [7] who applied pressure and employed the use of porous plates that allowed water to be extracted at a given pressure representing tension. The most commonly used and described method of measuring soil water potential in situ is through the use of tensiometers [8]. However, water potentials below approximately −0.085 MPa cannot be measured with tensiometers due to vaporization and cavitation of water within the device [9]. More recent work has extended the range of tensiometers by employing a polymer in place of water [10]; however, the range remains limited to soil water potentials much greater than −1.5 MPa.

Presently, the most commonly cited method for measuring moisture content (MC) at low water potentials in soilless substrates is the pressure outflow apparatus method described by Cassel and Nielsen [11]. The pressure outflow apparatus is a modified version of Richards and Fireman's pressure plates [7]. This method determines soil or substrate MC at a specified water potential and can be conducted in a relatively short period of time. However, previous research has pointed out inaccuracies with this method due to a loss of hydraulic connectivity between the water in the sample and the water in the plate when the soil or substrate dries [12–15]. This occurs because water moves in porous media primarily by displacement. Therefore, when the water column is interrupted, water movement ceases, preventing equilibrium between the applied pressure and the soil or substrate water potential.

Dewpoint hygrometry has also been used to measure water potentials of porous substances [16]. A dewpoint potentiometer utilizes hygrometry to determine water potentials of porous media via a chilled mirror to measure the dew point temperature in the headspace above a sample [17]. Recent research has shown the effectiveness of the dewpoint potentiometer for determining water potentials below −0.1 MPa for soils [18,19] and soilless substrates [20]. Moreover, dewpoint potentiometer measurements have demonstrated inaccuracies in pressure plate measurements for mineral soils [21,22]. Curtis and Claassen [23] compared dewpoint hygrometry to pressure plate measurements for inorganic amendments at water potentials of −1.5 MPa, demonstrating more precision with dewpoint hygrometry than with the pressure plates. Fields et al. [15] used dewpoint hygrometry to describe inaccuracies in measuring water retention of highly porous organic soilless substrate components with a pressure plate set at −1.5 MPa.

As improved water management continues to be an imperative focus for horticultural crop production, refining the characterization of water storage and availability in horticultural substrates is critical. Therefore, the objective of this research was to utilize dewpoint hygrometry to assess VWC of traditional soilless substrates at water potentials <-1.0 MPa. Additionally, we compared the VWC at substrate water potential values near −1.5 MPa measured through dewpoint hygrometry with values attained through other accepted methodologies in the literature and make inferences upon the viability of utilizing dewpoint hygrometry in soilless substrate science.

2. Materials and Methods

Preparation of Substrate Components and Composites

Substrate components tested were coconut coir pith (Densu Coir, Toronto, ON, Canada), horticultural grade Sphagnum peat moss (Premier Tech, Riviere-du-Loup, Quebec Canada), aged pine bark (PB; Pacific Organics, Henderson, NC, USA), pine wood chips (PWC), and shredded pine wood (SPW) with examples shown in Figure 1. The coir was hydrated from compressed bricks with tap water and then fluffed by hand to reconstitute the material. The peat was removed from the compressed bale, fluffed by hand, hydrated, and screened by hand through a 1.25 cm screen to prevent any larger aggregates (foreign debris) from being included in the sampling. Pine bark derived from harvested loblolly pine (*Pinus taeda* L.) trees was processed in a hammer mill through a 16 mm screen, windrowed, and allowed to age for nine months.

Figure 1. Examples of the base materials used in this research, including (**A**) Sphagnum peat moss; (**B**) coconut coir pith; (**C**) shredded pine wood; (**D**) pine wood chips; and (**E**) aged pine bark.

For the pine wood materials, 12-year old loblolly pine trees were harvested at ground level, de-limbed, and processed through either a wood chipper or a wood shredder with bark intact. The pine trees used to create PWC were harvested on 9 December 2011 and processed through a DR Chipper (18 HP DR Power Equipment, Model 356447; Vergennes, VT, USA) on 3 January 2012 to produce the coarse wood chips that were then hammer-milled (Meadows Mills, North Wilkesboro, NC, USA) through a 6.35 mm screen on 5 January 2012 yielding the final PWC product (Figure 2). The pine trees used to create the SPW were harvested on 12 December 2011, shredded in a Wood Hog shredder

(Morbark; Winn, MI, USA) on 9 January 2012 to create the coarsely shredded wood that was then hammer-milled through a 6.35 mm screen on 10 January 2012 yielding the final SPW product (Figure 2).

Figure 2. Pre and post hammer mill processing on the shredded pine wood (SPW) and pine wood chips (PWC). Shredded wood (**A**) passed through the hammer mill to produce SPW (**B**). Chipped pine wood (**C**) is passed through a hammer mill to produce PWC (**D**).

No additional screening was needed for the coir, PB, PWC, or the SPW. After acquiring, preconditioning, or creating the substrate materials all were placed in 60 L plastic bags, sealed, and stored in a controlled environment laboratory until experiment initiation.

On the day of sampling, bags were carefully turned upside down and mixed to ensure uniformity of the contents/materials, after which a representative sample of 14 L was collected. Moisture content (MC = mass of water/total mass) was measured for each material and adjusted to 55% by weight using procedures described by Fonteno and Harden [24]. Two substrate composites also tested in this experiment included a commercially available growing mix comprised of "Canadian sphagnum peat moss, pine bark, perlite, and vermiculite" (Fafard 4P; Sungro, Anderson, SC, USA) and an 80:20 (by vol.) peat: perlite substrate derived from peat (Berger Tourbe de Shaigne Blonde Golden; BP-P; Quebec Canada) that was taken from a compressed bale, loosened/fluffed by hand, and hydrated to 55% MC before being amended with horticultural grade perlite (Carolina Perlite Company, Gold Hill, NC, USA).

Measurements and Analysis. An initial test was conducted using a dewpoint potentiometer (WP4C, Decagon; Pullman, WA, USA) to determine water potentials for each substrate component and composite materials as they air dried. Based on these results, samples were prepared at target MC for each component and composite that fell within the water potential ranges of −1.0 to −2.0 MPa, and allowed to equilibrate for 24 h. Fifteen samples for each substrate component and twelve samples for each composite were evaluated. Five stainless steel sampling dishes (1.1 cm tall × 3.7 cm i.d.; Decagon; Pullman, WA, USA) were loosely filled to approximately half full (0.5 cm depth) from random locations in the prepared samples at each of the predetermined (through the initial test) MCs for each substrate. The dishes were immediately sealed with plastic lids and Parafilm® (American Can Co.;

Greenwich, CT, USA) to prevent evaporative water loss. The samples were then individually analyzed for substrate water potential utilizing the dewpoint potentiometer in precision mode. Only samples that resulted in measures between −1.0 and −2.0 MPa were utilized, resulting in six to twelve utilized measures (12, 9, 8, 7, and 6 measurements for coir, peat, shredded wood, pine bark, and wood chips, respectively) for the components (see example; Figure 3) and four and five samples for the two composites. The reduction in measures within the −1.0 to −2.0 MPa range in the composites is due to the heterogeneous nature of these materials resulting in less uniformity in drying.

Table 1. Estimated substrate-bound water contents, container capacity and available water for substrate components and composites determined via dewpoint hygrometry measured between −1.0 and −2.0 MPa.

Substrate	Surface-Bound Water (% vol. ± SD) [z]	Container Capacity [y] (% vol.)	Bulk Density (g/cm^3)	Available Water [x] (% vol.)
Coir	4.40 ± 0.30	75.2 b [w]	0.12 c	70.8
Peat	4.06 ± 0.36	80.1 a	0.09 d	76.0
Pine bark	7.35 ± 0.20	42.5 d	0.21 a	35.2
SPW [v]	4.77 ± 0.42	52.8 c	0.18 b	48.0
PWC [u]	4.60 ± 0.30	41.6 d	0.18 b	37.0
Mix 1 [t]	7.76 ± 1.62	59.3 c	0.10 d	51.5
Mix 2 [s]	8.42 ± 1.91	75.2 b	0.13 c	66.8

[z] Mean substrate-bound water content across substrate water potential between −1.0 and −2.0 MPa ± standard deviation (SD). [y] CC = container capacity values from NCSU porometer test. [x] AW = available water content calculated as difference between mean CC and SBW content. [w] Statistics preformed down columns using Tukey's HSD. Means with the same letter are not statistically different. [v] SPW = shredded pine wood made from loblolly pine (*Pinus taeda*) logs that were shredded prior to processing in a hammer mill through a 6.35 mm screen. [u] PWC = pine wood chips made from loblolly pine logs that were chipped prior to processing in a hammer mill through a 6.35 mm screen. [t] Mix 1 = Composite of Peat:perlite 80:20 (by vol.) [s] Mix 2 = Fafard 4P (Sungro,/Anderson, SC, USA).

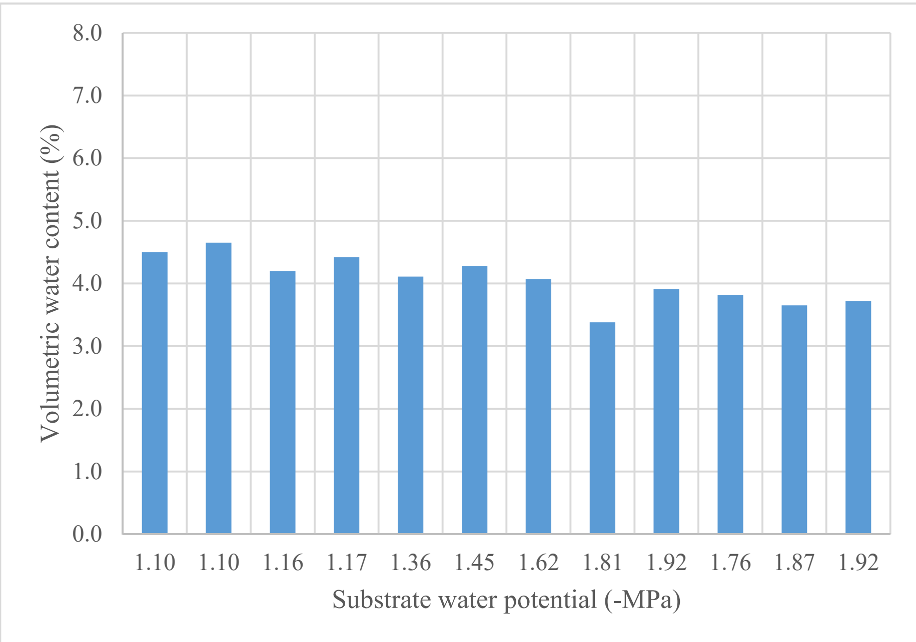

Figure 3. Example of individual sampling measurements of coconut coir. Variation of volumetric water content (VWC) was <1%. Data used to calculate values presented in Table 1.

Subsequently, mass wetness (MW = mass of water/mass of solid) was determined by placing the samples in a drying oven at 105 °C for 48 h to attain dry weights. Mass wetness for the samples was transformed to volumetric water content (VWC = volume of water/volume total) through: MW × Db of the material/density of water (1 g/cm^3) = VWC. Since both VWC and water potential were measured (i.e., neither were precisely controlled), values for both are presented and discussed according to their range and average. Bulk density and container capacity (CC) values were obtained using the NCSU porometer analysis following procedures of Fonteno and Harden [24] on three samples for each substrate. The values for VWC corresponding to the water potential range of −1.0 to −2.0 MPa were used as an estimate for soil-bound water and subtracted from the CC obtained from porometer analysis to obtain an estimate of available water holding capacity.

3. Results and Discussion

3.1. Estimating Water Availability at Low Water Potentials

Values for substrate-bound water obtained for all substrate components tested across the range of −1.0 MPa to −2.0 MPa were generally between 3% and 5% (Table 1), with PB providing the highest VWC at 7 to 8%. The PB had a higher VWC within the −1.0 to −2.0 MPa substrate water potential range likely resulting from reduced uniformity in the pore size distribution, as well as increased intraparticle porosity. As substrate water potential decreased, increased quantities of water became trapped within bark particles, thus limiting the water loss from the material. Furthermore, the majority of the accessible water present in the substrate at water potentials <−1.0 MPa exists primarily as hygroscopic water (water that is bound to particle surfaces). Previous research has demonstrated that at much higher substrate water potentials (i.e., −10 to −300 hPa or −0.0001 to −0.03 MPa) the VWC of PB is much lower than the other materials in this study [25]. This is likely from dual-porosity that is more evident in the PB than the other materials. Large pores created by irregular and large particles in PB readily drain at higher substrate water potentials, with smaller pores being either inaccessible or held more tightly at substrate water potentials between −1.0 and −2.0 MPa. The two composite substrates had similar VWCs (5 to 11%) at substrate water potentials in the range of −1.0 to −2.0 MPa (Table 1). These were only slightly larger than the other substrates, which indicates that the primary components in these substrates (i.e., peat or pine bark) dominate the hydraulic characteristics of the composites.

As expected, there was a large range in CC among the substrate materials and composites (Table 1). While many factors influence the CC of the substrate, the similarity between PB and PWC is likely a result of particle size and shape. Peat, coir, and SPW are more fibrous in structure, while PB and PWC had “plate-like” and “blockular” structure, respectively. The difference in particle size and shape can influence pore distribution and connectivity which has a great influence on water retention and CC, due to changes in the ratio of gravitational to capillary pores. Similar CC between the coir and Mix 2, as well as between SPW and Mix 1 highlight the similarities between fibrous materials and fiber-dominated mixtures (Table 1).

The estimated AW storage capacities for both peat and coir were >70% by volume. SPW, PWC, and PB had much lower AW (approx. 48%, 37%, and 35%, respectively). The differences in AW were primarily due to differences in CC, as there was little (<4%) difference observed in SBW among components. Moreover, by calculating the proportion of the water at CC that is AW (i.e., AW/CC from Table 1) coir, peat, SPW, and PWC are similar 94.1%, 94.9%, 90.9%, and 88.9%, respectively). However, the proportion of CC that is AW in PB is much lower at 82.7%. From data presented herein, PWC would appear to have similar properties to more traditionally used greenhouse substrate aggregates, such as PB and perlite. The SPW possessed a similar VWC at low substrate water potentials, yet a significantly greater CC, yielding increased AW (Table 1), which allows it to be incorporated into a substrate to increase drainage, while still retaining moisture needed for plant growth.

A review of the literature was performed and selected references associated with measuring soilless substrate VWC at substrate water potentials of −1.5 MPa were included in Table 2. The current accepted normal range of SBW is 23 to 35% by volume [26]. In fact, current best management practices for nursery growers recommend substrate SBW between 25 and 35% by vol. [27]. This acceptability range is further evidenced as much of the previous research utilizing ceramic pressure plates identifies commonly used substrates as having SBW within these ranges (Table 2). For example, Wright and Browder [28] reported SBW of PB as 26.6% and pine tree substrate at 23.6% (by vol.), respectively. This may be a significant overestimation of SBW (26.6% and 23.6% by vol. as compared to 7.5% and 4.8% by vol.), and therefore a large underestimation of AW (~20% by vol.) for these substrate materials. Water measurements (at −1.5 MPa) as high as 39.0% by volume have been reported in PB substrates using ceramic pressure plates [29]. With previous reports of miscalculations of soilless substrate SBW through ceramic pressure plate analysis at tensions <−1.0 MPa [12–15], it is entirely possible that many values within the literature are overestimating SBW.

Table 2. Survey of soilless substrate VWC at substrate water potentials of −1.5 MPa as measured through pressure plate extractors.

Publication	Material	Reported VMC (% vol.)
Altland and Krause [30]	Pine bark	29.9
	Pine bark: pine wood (1:1)	26.4
	Pine wood	24.2
Bilderback et al. [26]	Pine bark	33
	Pine bark: sand (4:1)	25
	Pine bark: peat moss (9:1)	32
	Pine bark: perlite (7:3)	33
	Pine bark: soil (9:1)	26
	Fir bark: peat: pumice (1:1:1)	25
Fonteno and Bilderback [13]	Pine bark	35.2
	Pine bark: sand (4:1)	35.6
Gabriel et al. [31]	Douglas fir bark	23
	Douglas fir bark: peat (7:3)	21
	Douglas fir bark: pumice (7:3)	25
Herring et al. [32]	Swine lagoon compost	28.7
	Pine bark fines-based potting mix	29.4
	Peat-based potting mix	27.5
Jackson et al. [33]	Pine bark	34.3
	Pine bark: clay (8:1)	31.6
	Pine bark: mortar sand (8:1)	27.3
Londra et al. [34]	Peat	13.1
	Peat: perlite (3:1)	12.3
	Coir	13
	Coir: perlite (3:1)	13
Milks et al. [35]	Peat: vermiculite	20
Niemiera et al. [29]	Pine bark	39
	Pine bark: sand (9:1)	27
	Pine bark: sand (5:1)	33
Owen, Jr. et al. [36]	Pine bark + clay	25
	Pine bark + sand	24
Owen, Jr. et al. [37]	Pine bark	38
	Pine bark + 12% mineral aggregate	36
Tyler et al. [38]	Pine bark	31.4
Warren et al. [39]	Pine bark	29
	Pine bark: cotton stalk/swine compost (85:15)	30
Wright et al. [40]	Peat:perlite:vermiculite: bark (45:15:15:25)	22
	Pine tree substrates	22
Write and Browder [28]	Pine bark	26.6
	Pine wood chips	23.6
	Pine wood chips: pine bark (3:1)	25

Previous research from the authors of this publication involved utilizing dewpoint hygrometry to assess the water potential of substrate components and field soils that had been squeezed to −1.5 MPa on ceramic plates [15]. The authors found that the water in the mineral soil samples did equilibrate at ~−1.5 MPa; however, the hydraulic connection between the coarse substrate components (bark, peat, and perlite) was broken at approx. −0.3 MPa, preventing additional water loss from the samples (Figure 4). Further investigation in that research showed that when peat and pine bark samples were squeezed at −0.1 and −0.3 MPa, the assessed water potential was close to the applied pressure. This leads the authors to believe that highly coarse substrate materials are not coming to equilibrium with pressures exceeding 0.3 MPa in traditional pressure plate extractors. This information further supports the hypothesis that the pressure plate analysis is overestimating water in samples at very low substrate water potentials.

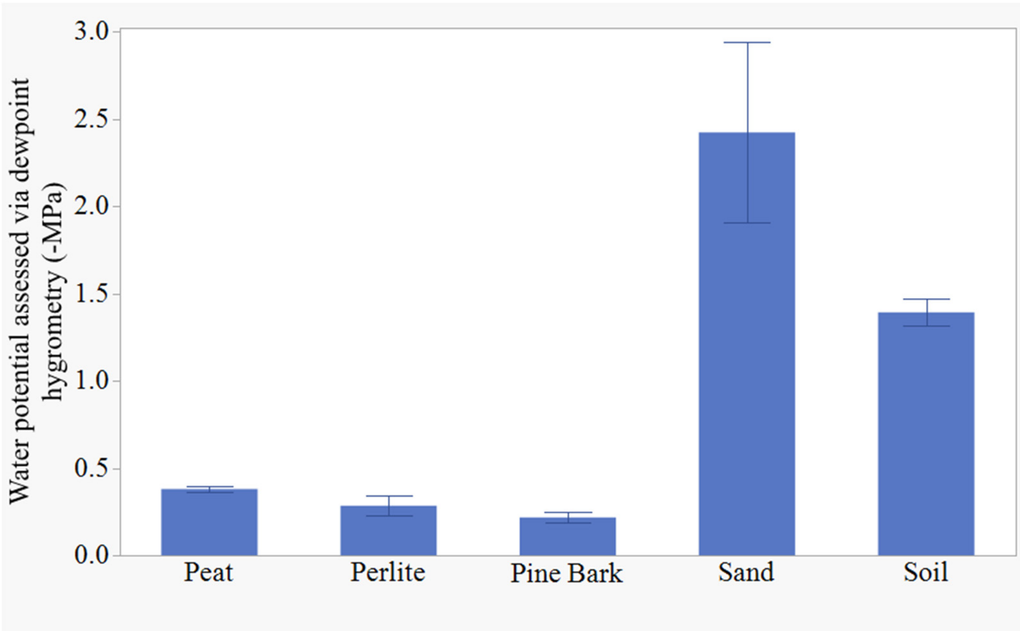

Figure 4. Substrate water potential of individual substrate and soil components assessed via dewpoint hygrometry, after being squeezed at −1.5 MPa on ceramic pressure plates in a volumetric pressure plate extractor. Data utilized from Fields et al., 2013 [15].

3.2. Gravimetric vs. Volumetric Water Contents

The authors also suggest a paradigm shift in discussing moisture contents that evolved during this work. The term used to describe the amount of moisture in a substrate had two forms: MC (expressed on a weight basis) and VWC (expressed on a volume basis). Initial moisture content for substrates is usually expressed as MC; however, almost all discussion of water content as a result of irrigation is expressed in terms of VWC. The moisture contents in these experiments were considered using both forms. In this case, MC was converted to VWC for comparisons in the table and figures (using yet another measure, MW). For example, coir at −1.5 MPa water potential has a resulting VWC of 7.62% (Table 1), which is equivalent to MC of 50% by weight. During the initial potting of most greenhouse crops, it is important to have adequate moisture in the substrate [27], and generally speaking, many growers tend to use ~50% MC substrates for planting. These results suggest that at this MC, coir is already at a water potential <−1.0 MPa, within the currently accepted range of plant unavailable water. Kiehl et al. [41] showed water stress symptoms occurring in plants at −16 kPa, much less negative than the −1.0 MPa of coir at 50% MC. These high (50%) MC values convert to much lower VWC values due to the very low bulk density of organic components. Moisture contents of 50% are considered to be heavy for transportation, in fact, coir is normally dried, compressed, and formed into blocks for shipping [42]. Peat is normally compressed two to three times and bailed at a MC of about 20–25% (personal observation) for shipping purposes, which is significantly lower than at substrate water potential of −1.5 MPa (37% MC). This establishes that not only is proper hydration of substrates important for potting/planting, but previously accepted MC levels are essential in the plant unavailable range. This also implies that recently potted plants should not be allowed to "sit" for prolonged periods of time before initial hydration (i.e., water) is applied.

4. Conclusions

The use of dewpoint hygrometry allowed estimates of soil-bound water in the water potential range (1.0 to 2.0 MPa) typically considered plant unavailable. These estimates are much lower than values previously reported for similar substrate components using pressure plates. The authors agree that problematic measures <−1.0 MPa can potentially overestimate SBW due to reported issues associated with highly porous organic materials in pressure plate analysis. As such, it is important that more efforts are utilized to investigate SBW from a substrate standpoint and identify more precise methods of analysis to truly identify substrate water relations at low water potentials. The use of dewpoint hygrometry has the potential to improve the estimation of SBW for substrate analysis. If further investigations find that dewpoint hygrometry measures are in fact accurate, best management practices and acceptable ranges should be updated.

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