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Hydraulic Performance of Horticultural Substrates—1. Method for Measuring the Hydraulic Quality Indicators

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Abstract: Besides nutrient composition, the hydraulic performance of horticultural substrates is a main issue for evaluating their quality for horticultural purposes. Their water and air capacity and their suitability for transporting water are important hydraulic quality indicators. Shrinkage and water repellency could have a negative impact on storing and transporting water and solutes. The commonly used methods and devices for quantifying the water retention properties of horticultural substrates (sand box, pressure plate extractor) are outdated. The measurements are time-consuming, the devices are expensive, and the results are affected by uncertainties. Here, the suitability of the extended evaporation method (EEM) and an associated HYPROP (HYdraulic PROPerty analyser, device was successfully tested for very loosely-bedded horticultural substrates. EEM and HYPROP enabled the simultaneous and effective measurement of the water retention curve and the unsaturated hydraulic functions. The measurement time of horticultural substrates ranges between 7 and 10 days. Furthermore, the shrinkage properties and the water rewetting time can be measured with the HYPROP system. Results using 18 horticultural substrates are presented. These results are discussed and compared with natural organic and mineral soils showing the specific hydraulic performance of substrates for horticultural applications.

Keywords: horticultural substrates; growing media; hydraulic properties; water retention curve; unsaturated hydraulic conductivity; water repellency; water drop penetration time; shrinkage; extended evaporation method (EEM); HYPROP

1. Introduction

Horticultural substrates are specially designed media for horticultural applications. Bog peat is the main basis for creating horticultural substrates [1,2]. Special organic and mineral ingredients are added to improve the physical and technological properties of the substrates. Besides the nutrient composition, the hydraulic performance of horticultural substrates is a main issue for evaluating their quality for horticultural purposes. The water and air capacity and suitability for transporting water are important hydraulic quality indicators [1–6]. The basic properties are the water retention curve and the hydraulic conductivity function. Shrinkage and water repellency could have a negative impact on storing and transporting water and solutes [1,7].

The measurement of the water retention curve of horticultural substrates is generally executed with the sand box and the pressure plate extractor [1,8,9]. These methods and devices are outdated, the measurement is time-consuming, the equipment is expensive, and the results are affected by uncertainties [10]. Only a few unsaturated hydraulic conductivity measurements in substrates have been presented, but they are required for an overall evaluation of horticultural substrate quality [1,11]. In some cases, the one-step outflow method has been used [2,12]. Raviv and Lieth [1] concluded that there is a lack of technologies and methods for the effective physical characterization of substrates in horticulture.

The extended evaporation method (EEM) and an associated HYPROP (HYdraulic PROPerty analyzer [13]) system enables the simultaneous measurement of the hydraulic functions, the water retention curve, and the hydraulic conductivity function. Here, the suitability of the EEM and the HYPROP was tested using very loosely-bedded horticultural substrates. Furthermore, the HYPROP was used to measure the shrinkage behaviour and the water rewetting properties of the horticultural substrates. These results are discussed and compared with natural organic and mineral soils, showing the specific performance of horticultural substrates for horticultural applications.

2. Experimental Section

2.1. Samples and Preparation

The hydraulic measurements were conducted on 18 commercial horticultural substrates and compared with 10 mineral and organic soils (Table 1). The horticultural substrates mainly consisted of 30% to 100% of bog peat (degree of decomposition between H3 and H7 [14], and different proportions of organic residuals (garden (G) and forest (F) compost), coir (Co) and mineral additives such as perlite (P), lime (K), clay (C) and sand (S). One of the horticultural substrates (no. 6) was totally free of bog peat. The natural soils are not used for horticultural purposes, and were only collected and analysed to show their hydraulic differences to the special commercial horticultural substrates. The fen soil material was collected from Muencheberg, Rotes Luch, Brandenburg, Germany. The degree of decomposition was quantified according to Von Post [14]. The mineral soils were formed by glacial processes and were collected at different arable sites in the state of Brandenburg, Germany.

Table 1. Collection of horticultural substrates (HS) and fen samples.

HS No.	Ingredients, Texture Class	Ash Content (%)	C_{org} (%)
	Horticultural substrates		
1	Hh (H3–H8), R, G	68.1	
2	Hh (H2–H4) H7–H9, G, R	16.8	
3	Hh (H2–H5), P, C, K	35.1	
4	Hh (H3–H8), R, G, P, C, K	21.4	
5	95% Hh (H3–H7), P, Co	24.4	
6	R, C, Co, Guano	25.3	
7	90% Hh (H4–H8), 10% C, K	41.0	
8	Hh (H3–H8), C,P	35.9	
9	75% Hh (H3–H5 and H6–H7), Co, C, K	25.1	
10	80% Hh (H3–H5 and H6–H7), Co, C	39.9	
11	Hh (H2–H5), G, R, P, C, K	48.3	
12	Hh (H3–H8), G, R, P, C, C	42.7	
13	Hh (H3–H5 and H7–H9)	15.1	
14	Hh (H2–H5), G, R, K	35.8	
15	Hh (H3–H8), G, P, K	10.8	
16	60% Hh (H3–H5 and H6–H7), R, G, Co, K	25.5	
17	60% Hh (H3–H5 and H6–H7), Co, C, P	42.8	
18	50% Hh (H3–H5), G, R, C	36.2	
	Natural organic and mineral soils		
19	Fen peat (Hn, H7)	55.0	
20	Half-fen (Aa)		11.6
21	Sand (Ss, strong humic		2.9
22	Weak silty sand (Su2)		0.9
23	Weak loamy sand Sl2		1.0
24	Medium loamy sand (Sl3)		1.1
25	Strong loamy sand (Sl4)		1.2
26	Medium clayey silt (Ut3)		1.3
27	Medium sandy loam (Ls3)		1.5
28	Sandy clayey loam (Lts)		1.6

Hh—bog peat, H degree of decomposition; R—compost of forest residuals; G—compost of garden residuals; Co—coir (raw coconut fibre); P—perlite; K—lime; C—clay; S—sand; Hn—fen peat; C_{org}—organic carbon; Texture class acc. to Boden, A.G. [15].

Sample preparation: a plastic pipe (diameter: 15 cm, height: 65 cm) was loosely filled with the substrate up to 5 cm below the upper edge. Water was added at the surface until water left at the bottom of the pipe. The pipe was placed for 2 days in a pan with a 3-cm water level. The substrate compacted itself hydraulically and after 2 days the capillary equilibrium was reached. At this time, the tension at the surface layer was about 50 hPa. The substrate material of the upper 5 cm layer of the pipe was taken, mixed and used to loosely fill 250 cm^3 HYPROP steel cylinders. During the filling procedure, the cylinder was stamped 10 times. The prepared sample was saturated and ready for the hydraulic measurements with the HYPROP system. This procedure was derived from DIN EN 13041 [9] and Verdonck and Gabriels [16] and guarantees a high reproducibility. It enables the hydraulic comparability of growing media though the substrates in the cylinder are of different basic moistures.

2.2. Hydraulic Criteria

The hydrological evaluation of the suitability of the tested substrates for horticultural applications depends on their hydraulic properties and the kind of cultivation (containers with different heights or bed cultivation). The most important aspects are (i) the amount of easily plant-available water (EAW) and (ii) the air capacity depending on the kind of cultivation. The capillary rise is an additional indicator for characterizing transport properties. The (iv) rewetting time and (v) shrinkage dynamics could negatively influence hydraulic substrate quality. In this study, the evaluation was carried out as an example of growing in 20-cm-high containers (P20).

2.3. Measurement of the Water Retention Curve and the Unsaturated Hydraulic Conductivity Function

The extended evaporation method [10] was tested for the very loosely-bedded horticultural substrates. The EEM enables the simultaneous measurement of the water retention curve and the hydraulic conductivity function. Using new cavitation tensiometers and applying the air entry value of the tensiometer's ceramic cup, it allowed the range to be extended almost up to the wilting point. The measurements were carried out using the HYPROP system. HYPROP [13] is the commercial device used to implement the EEM. The total measurement time depends on the soil or substrate and the evaporation conditions and ranges between 3 and 10 days. Multiple samples can be measured simultaneously.

2.3.1. Short Description of the Procedure

The substrate samples were slowly saturated with water. Two tensiometers were inserted from the bottom and the core was sealed at the bottom by clamping the cylinder with the assembly. The core was placed on weighing scales, and the mass and pressure conditions in the soil core were controlled online. The soil surface was exposed to free evaporation and the measurement cycle started. There was no uncontrolled water loss, not at the bottom and not at the surface. Figure 1 shows the principle of the experimental setup. Tensions and the sample mass were recorded at selected time intervals. The hydraulic gradient was calculated on the basis of the tensions recorded during the time interval. The water flux was derived from the associated soil water volume difference. Individual points on the water retention curve were calculated on the basis of the water loss per volume of the sample at a time t_i and were related to the mean tension in the sample at this time. The unsaturated hydraulic conductivity (K) was calculated according to the Darcy-Buckingham law (Equation (1)).

$$K(\Psi_{mean}) = \frac{\Delta m}{a A \, \Delta t \, i_m} \quad (1)$$

where Ψ_{mean} is the mean tension over the upper tensiometer at position z_1 (3.75 cm above the bottom of the sample) and the lower tensiometer at position z_2 (1.25 cm above the bottom), geometrically averaged over a time interval of $\Delta t_J = t_{i+1} - t_i$, with $i = 1 \ldots n$, $j = 1 \ldots n - 1$; Δm is the sample mass difference in the time interval (assumed to be equal to the total evaporated water volume ΔV_{H2O} of the whole sample in the interval); a is the flux factor (in the case of rigid soils a = 2); A is the cross-sectional area of the sample; i_m is the hydraulic gradient averaged over the time interval.

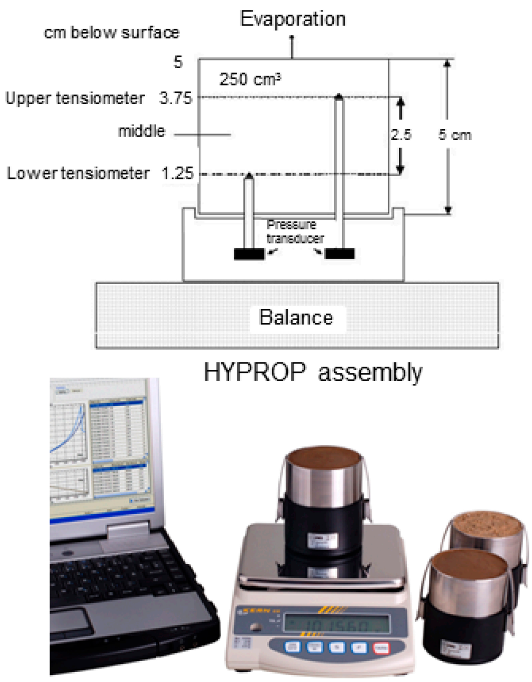

Figure 1. Schematic illustration of the evaporation method (Photo: UMS GmbH, Munich, Germany).

Data points of the water retention curve were pairs of mean tension at times t_i and t_{i+1} for $i = 1 \ldots n$ and the corresponding volumetric water content. The soil was assumed to be rigid. An EEM data set of a single sample consisted of multiple user-defined water retention and hydraulic conductivity data pairs. At the end of the measurement cycle, the residual amount of storage water was derived from the water loss upon oven drying (105 °C), and the initial water content was calculated. The dry bulk density was derived from the dry soil mass. Furthermore, soil hydraulic functions could be measured under consideration of shrinkage [17].

2.4. Rewetting Properties

The Water Drop Penetration Time Method (WDPT) [18] was used in this study to quantify the rewetting properties. The method is based on the time taken for a drop of water to infiltrate into the substrate. Using a pipette, one drop of water was added to the sample and the water penetration time was measured. The measurement was executed at different times during the evaporation experiment to gain WDPT values at tensions of approximately 100 hPa. The measurement was repeated 3 times to calculate the average value. This procedure is easy to handle and does not need a great deal of technical effort.

2.5. Shrinkage Measurement

Shrinkage was estimated during the evaporation experiment. The diameter of the sample's surface was measured at a tension of about 100 hPa using a calliper. The shrinkage from the bottom to the top of the sample is linear in this tension range [17]. In conclusion, the shrinkage of the sample was calculated (Equation (2)). Isotropic conditions were assumed.

$$V_s = \frac{\pi}{4} * \left[\frac{d_i + d_s}{2}\right]^2 * h_s \tag{2}$$

where V_s is the volume of the shrunken sample, d_i is the initial sample diameter, d_s is the diameter at the sample's surface at 100 hPa and h_s is the height of the shrunken sample.

A more accurate but also more complicated method is described by Schindler et al. [17]. Here the shrinkage was measured online during the evaporation process.

3. Results and Discussion

The water retention curves of all tested natural mineral and organic soils and three example horticultural substrates are illustrated in Figure 2. The easily plant-available water (EAW) in the tension range between 20 and 100 hPa and the air capacity (Air) are marked in the figure. All other required water and air capacities (for different kinds of cultivation) could be calculated based on these functions. As expected, due to the low dry bulk density, the saturated water content of the horticultural substrates was very high (Table 2). It varied between 71.8% (HS1) and 87.1% (HS6) by vol., averaged 82.4% by vol., and was comparable to the fen peat (Hn, 84.0% by vol.). However, the EAW and the air capacity demonstrated the special performance of horticultural substrates for horticultural applications. The tested horticultural substrates provided between 26.5 and 44.2 mm of water per 10 cm substrate depth (an average 30.8 mm). The natural mineral and organic soils could only store between 5.7 and 20.7 mm. However, what was more dramatic was the air capacity. The horticultural substrates provided an average 10.4 vol. % air with a major variation between the single samples (HS13: 2.7 vol. % and the peat-free HS6: 31.7% by vol.). Only about half of the tested substrates provided sufficient air (threshold value 10 vol. %, according to Raviv and Lieth [1]). The natural soils were even worse (0.6%–4.6% by vol., an average 2.0% by vol.) and were far from achieving the threshold value of 10%. The suitability for storing and transporting water and solutes is strongly influenced by shrinkage and rewetting properties [1,2]. The rewetting properties of most substrates were sufficient, with the exception of HS4, HS12 and HS14 which exceeded the threshold value for the WDPT of 5 s [19]. The shrinkage also showed great variability, ranging between 0.4 and 9.1 vol. % within the substrates. Only about half of the samples achieved or exceeded the threshold value for the capillary rise of 30 cm height for a 5 mm·day^{-1} rate. The same situation was observed for the mineral sandy (Ls3) and clayey loam (Lts) substrates.

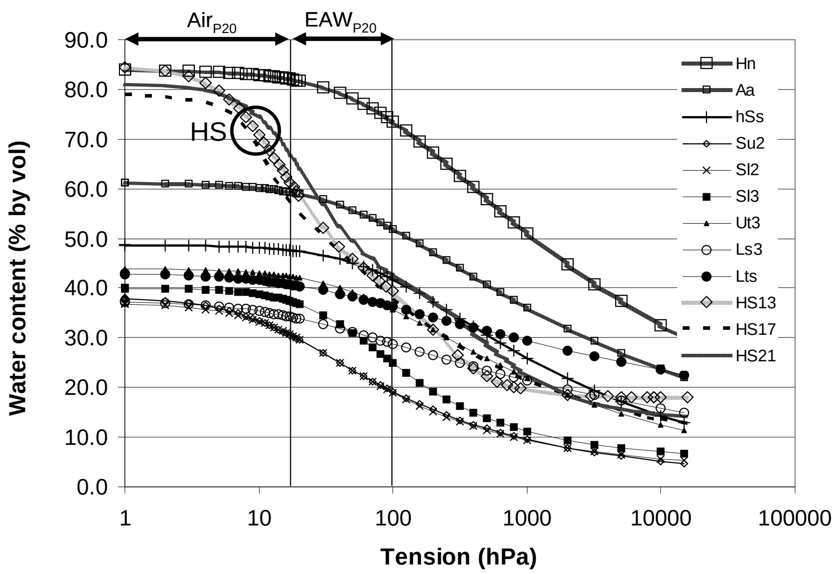

Figure 2. Water retention curves of the natural mineral and organic soils and examples of three horticultural substrates (HS), Air$_{P20}$—average air volume in 20-cm-high containers, EAW$_{P20}$—easily plant-available water in 20-cm-high containers.

Table 2. Hydraulic properties of the horticultural substrates.

No.	Θ_s	FC	Air_{P20}	EAW_{P20}	S	DBD	CR_5	WDPT
	Vol. %					$g \cdot cm^{-3}$	cm	Sec.
Horticultural substrates								
1	71.8	38.7	9.3	28.2	2.1	0.43	10.1	0.1
2	86.0	48.0	6.5	36.6	6.2	0.17	45.7	1
3	79.6	46.4	9.4	27.9	5.4	0.30	54.7	0.1
4	79.0	46.2	11.8	26.7	3.3	0.26	26.7	15
5	86.2	45.1	11.7	34.4	2.1	0.20	42.9	2
6	87.1	31.6	31.7	26.7	0.4	0.18	17.9	0.1
7	84.2	53.8	4.5	31.1	9.1	0.21	24.4	1
8	81.2	50.6	5.7	29.1	6.6	0.25	45.7	0.1
9	80.7	38.8	13.9	33.5	0.8	0.22	29.3	0.1
10	84.4	44.1	13.6	31.4	6.2	0.18	29.3	0.1
11	83.1	54.7	7.2	26.5	6.2	0.31	13.1	2
12	75.8	40.8	6.8	32.8	1.0	0.30	26.7	6
13	84.5	55.1	2.7	32.5	0.6	0.21	47.7	1
14	78.8	43.2	11.6	29.2	0.8	0.28	15.9	6
15	83.4	52.0	6.9	29.6	7.0	0.19	36.4	2
16	81.1	39.8	13.7	31.5	3.3	0.19	12.7	1
17	80.8	48.8	13.8	32.1	6.2	0.23	29.3	0.1
18	81.0	47.3	7.6	30.6	7.0	0.26	79.9	2
Natural organic and mineral soils								
19	84.0	77.2	1.1	9.4	7.2	0.43	80	6
20	61.3	54.9	1.1	8.2	4.1	1.05	56	9
21	48.7	44.3	0.6	20.7	2.1	1.35	51	3
22	38.2	22.2	4.6	14.5	nm	1.63	32	nm
23	36.9	22.2	3.6	14.4	nm	1.66	46	nm
24	40.0	29.4	1.4	13.8	nm	1.58	123	nm
25	34.5	25.6	3.0	7.6	nm	1.72	30	nm
26	43.9	38.4	0.9	7.3	nm	1.48	61	nm
27	37.5	30.5	2.0	6.7	nm	1.64	4	nm
28	43.0	37.8	1.4	5.4	1.9	1.50	17	nm

Θ_s—Water content at saturation; FC—Field capacity at pF 1.8; Air_{P20}—air capacity in a 20-cm-high container; EAW_{P20}—easily plant-available water in 20-cm-high containers; S—shrinkage at a tension of 100 hPa; DBD—Dry bulk density; CR_5—steady-state capillary height for a 5 mm·day^{-1} rate; WDPT—water drop penetration time in seconds at 100 hPa; nm—not measured.

The results for the specially composed horticultural substrates in this study showed their superiority for horticultural applications. However, there were differences in their hydraulic suitability. Generally, the water demand in shallow containers was sufficiently covered by most samples. The most sensitive element, however, was the air supply, especially for cultivation in shallow containers. High water penetration times and substrate shrinkage is of key relevance for sustainable, resource-saving water and nutrient management.

4. Conclusions

The hydraulic evaluation of horticultural substrates is an important part of an overall assessment of their suitability for horticultural applications. The applied hydraulic measurement techniques and methods (EEM, HYPROP, WDPT) proved to be suitable for characterizing the hydraulic properties of horticultural substrates. Lack of air was the main critical factor. The results with the specially composed horticultural substrates in this study showed their superiority for horticultural applications. The development of a rating system to evaluate the hydraulic quality of horticultural substrates should be the topic of further studies.

Author Contributions: Uwe Schindler made the HYPROP measurements and evaluated the results. Lothar Müller made result evaluation. Frank Eulenstein was responsible for selecting the samples and was involved in the discussion and evaluation of the results.

Conflicts of Interest: The authors declare no conflict of interest.

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