horticulturae

MDPI

Article

Hydraulic Performance of Horticultural Substrates—2. Development of an Evaluation Framework

Uwe Schindler * and Lothar Müller

Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Landscape Hydrology, Eberswalder St. 84, Muencheberg D15374, Germany; mueller@zalf.de

* Correspondence: uschindler@zalf.de; Tel.: +49-33-4328-2353; Fax: +49-33-4328-2300

Academic Editors: Varit Srilaong, Mantana Buanong, Chalermchai Wongs-Aree, Sirichai Kanlayanarat and Douglas D. Archbold

Received: 2 December 2015; Accepted: 5 July 2016; Published: 30 December 2016

Abstract: Sustainable, environmentally friendly and resource-saving water and nutrient management in horticulture requires knowledge of the hydraulic suitability of horticultural substrates for each specific application. The aim of this study was to develop methods and a rating framework to assess the hydraulic performance of horticultural substrates. The hydraulic criteria related to high-quality horticultural substrates were defined as the amount of easily plant-available water (EAW) in the tension range between 10 and 100 hPa, the air capacity and the height of capillary rise. Limiting factors could be water repellency effects and shrinkage. The rating framework consisted of 5 classes between non-satisfactory and very good. The assessment of the hydraulic performance was split for the cultivation into 10-, 20-, and 30-cm-high containers. It was tested on 18 commercial substrates. More than 70% of the tested substrates revealed scores between very good and good. About 30% were evaluated as medium or satisfactory. The most critical aspect was the low air capacity in shallow containers. Shrinkage and water repellency sometimes strongly diminished the score. Both the measurement methods for quantifying substrate hydraulic properties and the evaluation procedure proved applicable. The impact of different ingredients and the composition of substrates of their hydraulic performance should be statistically analysed in further studies.

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

1. Introduction

Horticultural substrates, also referred to as growing media, potting soils and gardening or soilless substrates, are widely used as a basis for vegetable and flower production in horticulture and private households, either in greenhouses or under field conditions. They are created as a composition of different ingredients. In most cases, bog peat, mainly consisting of sphagnum moss, is used as the basis for producing horticultural substrates [1,2].

Besides nutrient composition, the hydraulic performance of horticultural substrates is a key issue for evaluating its quality for horticultural purposes. The water and air capacity and the suitability for transporting water are important hydraulic quality indicators [1]. The basic properties are the water retention curve and the hydraulic conductivity function. Shrinkage and water repellency could have negative impacts on storing and transporting water and solutes [1,3]). Hydraulic data for only a few substrates have been reported [4–6]. In most cases the methods and devices used are outdated, the measurements have been time-consuming, the equipment is expensive and the results are subject to uncertainties [7]. Raviv and Lieth [1] concluded that there are a lack of technologies and methods for the effective physical characterization of substrates in horticulture. Many different horticultural substrates are available on the market. The declaration on the package generally provides information on the ingredients and the chemical composition. There is generally no information on physical properties such as the water and air capacity, water and solute transport, shrinkage, and rewettability. However, accurate hydraulic criteria, parameters and measurement data can improve the evaluation of the hydraulic performance of substrates in horticulture [1].

The aim of this study was the development of a rating framework to compare and to assess the hydraulic suitability of substrates used in horticulture.

2. Experimental Section

2.1. Hydraulic Quality Indicators

The hydraulic performance of substrates for plant production in horticulture depends on their capacity to store, transport and supply water, air and nutrients. The higher the water and air capacity and the transport properties of the substrate, the better is its performance for horticultural applications. The important hydraulic variables are the water retention curve and the hydraulic conductivity function [1]. Bulk density and sample preparation are key factors for hydraulic properties of substrates. The sample preparation method was derived from DIN EN 13041 [8] and [2] and guarantees a high reproducibility. It enables comparison of hydraulic properties of growing media even if the substrates are of different basic moistures.

The optimum water supply in horticulture depends on the crop and variety and is achieved in a tension range between 10 and 100 hPa [1,2]. A lower tension limit should guarantee sufficient air [1,9] to avoid any adverse impact on crop growth. According to Raviv and Lieth [1], the easily plant-available water capacity (EAW) should exceed 24% by vol. Higher water capacity is better, but a lower water capacity is defined as under-supplied. According to Raviv and Lieth [1], the air capacity should exceed 10% by vol. to avoid stress due to air limitations. Synonymous with air capacity are air space or air-filled porosity. All water- and air-related parameters in the paragraphs below are expressed as % by vol. The water and air capacities in containers depend on the water retention function and the height of the container. After free drainage, the air capacity is zero at the bottom. That means the substrate is saturated with water. The tension at the surface in hPa corresponds to the height of the container in cm. Heiskanen 1995 [10] Raviv & Lieth [1] concluded that the measurement of hydraulic parameters for describing and quantifying water and solute transport are heavily underrepresented in horticulture. Therefore, the capillary height calculated for a 5 mm·day^{-1} rate (CR_5) was used as an additional indicator for estimating the flow resistance and the hydraulic suitability and quality of the substrate reflecting the ease of exchange of water and nutrients in the growing layer. Due to the low transfer distances required, we defined the suitability of horticultural substrates as not limited for capillary heights greater than 30 cm. Limiting factors could be water repellency effects and shrinkage of the horticultural substrates. With reference to Blanco-Canqui and Lal [11] and Poulter et al. [12], the water drop penetration time (WDPT) should not exceed 5 s to avoid negative effects on water infiltration due to water repellency. Longer wetting times could be an indicator of rewetting limitations and preferential flow [13,14]. A shrinkage volume of 5% by vol. should not be exceeded to avoid adverse effects on plant growth and resource management.

2.2. Rating Framework

The hydraulic rating framework of horticultural substrates consisted of two parts: the rating of the basic soil hydrological properties (S_B, Table 1) and the rating of the limitations (S_L, Table 2). The easily plant-available water (EAW) and air capacity (Air) were assessed on a 5-point scale, and capillary rise (CR) on a 2-point scale. The water capacity depended on the storage volume and the thickness of the storage layer. The best score of the basic properties (EAW, Air, CR) was 5, and the poorest rating was 1. The limitations (WDPT and soil shrinkage) were assessed in a 3-point scale. The score of the limitations (S_L) ranged between 0 (no limitation) and 2 (strong limitation). Only the score of the most severe limitation was considered. In the case of a score of 2 for strong rewetting limitation (S_L_{WDPT}) and a score of 1for shrinkage (S_L_{S100}), the value 2 had to be considered. The total rating (S_T, Table 3) for the evaluation of the hydraulic performance of the substrates was calculated as the sum of the basic score S_B minus the score of the dominating limitation (S_L). The highest score was 12, the lowest was 1. The hydraulic rating in this study was calculated for horticultural substrates in 10-, 20- and 30-cm high containers (P10, P20 and P30, respectively).

Table 1. Rating scale of basic hydraulic requirements (Basic score (S_B)).

Parameter	Basic Score (S_B)				
	1	2	3	4	5
EAW [1] (% by vol.)	<12	12–16	16–20	20–24	≥24
Air capacity (% by vol.)	<2	2–5	5–8	8–10	≥10
CR_5 [2] (cm)	<30	≥30			

[1] Easily plant-available water; [2] CR_5—capillary height for a 5 mm·day^{-1} rate.

Table 2. Rating scale of hydraulic quality limitation scores (S_L).

Parameter	Limitation Score (S_L)		
	0	1	2
WDPT (in seconds) [1]	≤5	5–15	>15
S_{100} [2] (% by vol.)	≤2	2–5	>5

[1] WDPT—water drop penetration time at 100 hPa; [2] Shrinkage at 100 hPa.

Table 3. Total rating (S_T) of the hydraulic performance of substrates in horticulture.

Evaluation	Total Score (S_T)
Very good	≥10
Good	<10–>8
Medium	<8–>6
Satisfactory	<6–>4
Non-satisfactory	≤4

2.3. Substrate Samples and Hydraulic Measurements

As examples, the hydraulic quality indicators were determined for 18 commercial horticultural substrates (Table 4).

Table 4. Collection of horticultural substrates (HS).

HS No.	Ingredients, Texture Class	Ash Content (%)
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

Abbreviations: 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.

The substrates mainly consisted of 30% to 100% bog peat (degree of decomposition between H3 and H7, von Post, 1922 [15], and different portions 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 them (No. 6) was totally free of peat.

The water retention curve and the unsaturated hydraulic conductivity function were measured with the extended evaporation method (EEM) and the HYPROP system from saturation to close to the wilting point [7,16,17]. These functions were used for calculating the water (EAW) and air (Air) capacity and for quantifying the capillary rise (CR). The WDPT and shrinkage (S_{100}) were measured during the evaporation experiment at a tension of about 100 hPa [8].

3. Results and Discussion

According to Raviv and Lieth [1], the maximum tension for avoiding water stress was assumed to be 100 hPa. The height of the container markedly influenced the water and air capacity. The range of the easily plant-available water (EAW) and, especially, the air capacity for plant cultivation in the containers of varying heights differed strongly between the substrates. The EAW was evaluated as sufficient for most (more than 90%) substrates in the different containers, with the exception of HS6 which, at 10.7%, revealed an above-average low water storage capacity in P30. However, contrary results relevant to plant stress were measured for the air capacity. In P10, only HS 6 achieved and clearly exceeded the threshold value of 10%. Plants in all other substrates were strongly undersupplied with air. In P20 about half of the substrates revealed no air limitation, and in P30 only HS 13 was undersupplied with air. The capillary water transport was evaluated as sufficient for about half of the substrates. Only the substrates HS 1, 11 and 16 showed a considerable reduction of capillarity. The hydraulic performance (Table 5) of 11 substrates was negatively affected to different extents by shrinkage during drying, and only 3 samples showed an occurrence of water repellency.

Table 5. Hydraulic properties of the horticultural substrates.

HS No.	Θs	Air			EAW			CR_5	WDPT	S_{100}	DBD
		P10	P20	P30	P10	P20	P30				
	% by vol.							cm	sec	% by vol.	g·cm^{-3}
1	71.8	2.5	9.3	17.5	35.1	28.2	20.1	10.1	0.1	2.1	0.43
2	86.0	1.4	6.5	14.2	41.8	36.6	29.0	45.7	1	6.2	0.17
3	79.6	2.3	9.4	17.6	35.0	27.9	19.7	54.7	0.1	5.4	0.30
4	79.0	6.3	11.8	19.4	32.3	26.7	19.2	26.7	15	3.3	0.26
5	86.2	2.3	11.7	21.8	43.8	34.4	24.3	42.9	2	2.1	0.20
6	87.1	20.1	31.7	47.8	38.3	26.7	10.7	17.9	0.1	0.4	0.18
7	84.2	0.7	4.5	10.4	34.8	31.1	25.1	24.4	1	9.1	0.21
8	81.2	1.5	5.7	11.8	33.4	29.1	23.0	45.7	0.1	6.6	0.25
9	80.7	6.4	13.9	23.8	41.0	33.5	23.6	29.3	0.1	0.8	0.22
10	84.4	6.1	13.6	23.3	38.9	31.4	21.7	29.3	0.1	6.2	0.18
11	83.1	1.9	7.2	13.4	31.8	26.5	20.2	13.1	2	6.2	0.31
12	75.8	0.8	6.8	14.4	38.7	32.8	25.2	26.7	6	1.0	0.30
13	84.5	0.6	2.7	7.5	34.6	32.5	27.7	47.7	1	0.6	0.21
14	78.8	3.9	11.6	20.2	36.9	29.2	20.6	15.9	6	0.8	0.28
15	83.4	1.3	6.9	14.0	35.2	29.6	22.4	36.4	2	7.0	0.19
16	81.1	6.1	13.7	25.1	40.1	31.5	21.1	12.7	1	3.3	0.19
17	80.8	5.5	13.8	23.8	40.4	32.1	22.1	29.3	0.1	6.2	0.23
18	81.0	2.6	7.6	14.5	35.6	30.6	23.7	79.9	2	7.0	0.26

Abbreviations: Θs—saturated water content; Air—air capacity in 10, 20 and 30 cm high containers P; EAW—easily plant-available water; CR_5—steady-state capillary height for a 5 mm·day^{-1} rate; S_{100}—shrinkage at 100 hPa; WDPT—water drop penetration at 100 hPa; DBD—Dry bulk density.

The evaluation of the hydraulic performance of the substrates was split for cultivation in different high containers, as described in Tables 1–3 (Table 6). More than 70% of the tested substrates revealed scores between very good and good. About 30% of the substrates were evaluated as medium or satisfactory. The average score in P10 was 8.1 and was 9.0 in P20 and P30. However, there was a great variation between the substrates in the special container and between the containers of different heights. The score ranged from 12 (very good) for HS 5 in P20 and P30 to 5 (satisfactory) for HS 7 and 11 in P10. About 70% of the substrates revealed scores between good and very good. The most critical factor was the low air capacity in shallow containers. However, due to strong shrinkage or water repellency during drying, the score sometimes changed to medium or satisfactory. These processes could lead to reduced water and nutrient supply and solute leaching [11]. The addition of perlite and coir induced positive effects on the hydraulic performance. High amounts of bog peat tended to encourage shrinkage.

Table 6. Rating of the hydraulic performance of the horticultural substrates.

HS No.	Score_Basic Requirement S_B							Score_S_L		Score S_T		
	Air			EAW			CR_5	WDPT	S_{100}	P10	P20	P30
	P10	P20	P30	P10	P20	P30						
1	2	4	5	5	5	4	1	0	0	8	10	10
2	1	3	5	5	5	5	2	0	2	6	8	10
3	2	4	5	5	5	3	2	0	2	7	9	8
4	3	5	5	5	5	3	1	2	1	7	9	7
5	2	5	5	5	5	5	2	0	0	9	12	12
6	5	5	5	5	5	1	1	0	0	11	11	7
7	1	2	5	5	5	5	1	0	2	5	6	9
8	1	3	5	5	5	4	2	0	2	6	8	9
9	3	5	5	5	5	4	1	0	0	9	11	10
10	3	5	5	5	5	4	1	0	2	7	9	8
11	1	3	5	5	5	4	1	0	2	5	7	8
12	1	3	5	5	5	5	1	1	0	6	8	10
13	1	2	3	5	5	5	2	0	0	8	9	10
14	2	5	5	5	5	4	1	1	0	7	10	9
15	1	3	5	5	5	4	2	0	2	6	8	9
16	3	5	5	5	5	4	1	0	1	8	10	9
17	3	5	5	5	5	4	1	0	2	7	9	8
18	2	3	5	5	5	4	2	0	2	7	8	9

4. Conclusions

The hydraulic measurement techniques and methods (EEM, HYPROP, WDPT) used here proved to be suitable for characterizing the hydraulic properties of horticultural substrates as a basis for evaluating their hydraulic applicability for horticultural use. The appropriateness of the methods and the devices were tested and confirmed for 18 commercial horticultural substrates. The proposed evaluation framework provides an opportunity to compare the hydraulic properties of the substrates taking into account threshold values for the plant water and air supply.

Moreover, the gas diffusivity, respiration rate and hysteresis of the hydraulic functions should be taken into account for a better understanding of plant growth in horticulture [1,9]. The latter is of special importance in the low-tension range, because the drainage and the rewetting curves of the hydraulic functions could lead to different results and evaluations [17].

Irrigation of shallow containers should be carried out in a very sensitive manner. Water loss at the bottom of the container induces saturation. This behaviour is associated with lack of air in the container and could lead to growing stress and decreasing yields.

This study provides initial information about the hydraulic properties and the performance of some commercial substrates for horticultural applications. This kind of information is intended to expand our knowledge of substrate hydraulic properties and help evaluate substrate suitability in horticulture. Until recently, substrate buyers were not able to draw any conclusions regarding hydraulic properties on the basis of the declaration and the ingredients of the particular product they had bought. Therefore, statistical analyses of a large number of substrates with different amounts of bog-peat as well as those without peat involving various ingredients should provide real help. The proposed rating framework could be the basis of this evaluation.

Author Contributions: Uwe Schindler was responsible for the soil hydraulic measurements. Lothar Müller and Uwe Schindler developed the rating framework.

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

References

1. Raviv, M.; Lieth, J.H. *Soilless. Culture*; Elsevier Publications: London, UK, 2008; p. 608.
2. Verdonck, O.; Gabriels, R.I. Reference method for the determination of physical properties of plant substrates. II. Reference method for the determination of chemical properties of plant substrates. *Acta. Hortic.* **1992**, *302*, 169–179. [CrossRef]
3. Dekker, L.W.; Ritsema, C.J.; Oostindie, K.; Boersma, O.H. Effect of drying temperature on the severity of soil water repellency. *Soil Sci.* **1998**, *163*, 780–796. [CrossRef]
4. Fonteno, C.F. Problems & considerations in determining physical properties of horticultural substrates. *Acta Hortic.* **1993**, *342*, 197–204.
5. Bougoul, S.; Ruy, S.; de Groot, F.; Boulard, T. Hydraulic and physical properties of stonewool substrates in horticulture. *Sci. Hortic.* **2005**, *104*, 391–405. [CrossRef]
6. Paraskevi, A.L.; Psychoyou, M.; Valiantzas, J.D. Evaluation of substrate hydraulic properties amended by urea-formaldehyde resin foam. *Hortscience* **2012**, *47*, 1375–1381.
7. Schindler, U.; Durner, W.; Von Unold, G.; Mueller, L.; Wieland, R. The evaporation method—Extending the measurement range of soil hydraulic properties using the air-entry pressure of the ceramic cup. *J. Plant Nutr. Soil Sci.* **2010**, *173*, 563–572. [CrossRef]
8. DIN EN 13041. *Bodenverbesserungsmittel und Kultursubstrate—Bestimmung der Physikalischen Eigenschaften—Rohdichte (Trocken), Luftkapazität, Wasserkapazität, Schrumpfungswert, und Gesamtporenvolumen*; Beuth Verlag GmbH: Berlin, Germany, 2012.
9. Caron, J.; Pepin, S.; Periard, Y. Physics of growing media in green future. *Acta Hortic.* **2014**, *1034*, 309–317. [CrossRef]
10. Heiskanen, J. Physical properties of two-component growth media based on Sphagnum peat and their implications for plant-available water and aeration. *Plant Soil* **1995**, *172*, 45–54. [CrossRef]
11. Blanco-Canqui, H.; Lal, R. Extent of soil water repellency under long-term no-till soils. *Geoderma* **2009**, *149*, 171–180. [CrossRef]
12. Poulter, R.; Duff, A.A.; Bauer, B. Quantifying Surfactant Interaction Effects on Soil Moisture and Turf Quality. Horticulture Australia Ltd., 2009. Available online: http://www.deedi.qld.gov.au/ (accessed on 14 August 2015).
13. Bauters, T.W.J.; Steenhuis, T.S.; DiCarlo, D.A.; Nieber, J.L.; Dekker, L.W.; Ritsema, C.J.; Parlangea, J.-Y.; Haverkampe, R. Physics of water repellent soils. *J. Hydrol.* **2000**, *231*, 233–243. [CrossRef]
14. Ritsema, C.J.; Dekker, L.W. Water repellency and its role in forming preferred flow paths in soils. *Aust. J. Soil Res.* **1996**, *34*, 475–487. [CrossRef]
15. Von Post, L. Sveriges Geologiska Undersöknings torvinventering och nogra av des hittils vunna resultat (SGU peat inventory and some preliminary results). *Svenska Mosskulturforeningens Tidskrift Jonköping* **1922**, *36*, 1–37.
16. Schindler, U.; Doerner, J.; Müller, L. Simplified method for quantifying the hydraulic properties of shrinking soils. *J. Plant Nutr. Soil Sci.* **2015**, *178*, 36–145. [CrossRef]
17. Schindler, U.; Von Unold, G.; Müller, L. Laboratory measurement of soil hydraulic functions in a cycle of drying and rewetting. *Int. J. Emerg. Technol. Adv. Eng.* **2015**, *5*, 281–286.