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Hydraulic Performance of Horticultural Substrates—3. Impact of Substrate Composition and Ingredients

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Abstract: 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. They are created as a composition of different ingredients (bog peat, organic residuals, coir, perlite and other components). Hydraulic properties such as water storage capacity, air capacity, shrinkage behaviour, wettability or hydraulic conductivity are important variables for a comprehensive evaluation of the performance of horticultural substrates. A set of 36 commercial potting soils and substrates was selected and the hydraulic properties (water retention curve, unsaturated hydraulic conductivity function, capillary rise and shrinkage) were measured using the extended evaporation method (EEM). Additionally, the water drop penetration time was determined as a measure of wettability. The hydraulic performance of the horticultural substrates was evaluated. Generally, bog peat is the main component of horticultural substrates. Additionally, coir (raw coconut fibre), bark, different composts and mineral ingredients such as perlite, pumice, vermiculite, sand and others are used. The growing medium with the best hydraulic performance in this study revealed substrates composed of bog peat with added coir, perlite and organic residuals. Mineral ingredients in general decreased the content of easily available water but did not exhibit any significant effect on the other properties studied. However, the risk of a lack of air can be increased by the addition of clay. The presence of perlite had positive effects on the air content and the re-wettability. The presence of organic materials had significant and detrimental effects on the height of the capillary rise. We also found that some products declared as preferable for use in containers were better suited as substrates for bed cultivation. However, a comprehensive evaluation of the eligibility of horticultural substrates in horticulture requires not only hydraulic measurements but also growing experiments and an assessment of their chemical, biological and technological suitability.

Keywords: 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-grown conditions [1–3]. 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 [2,3].

There are many different substrates for horticultural applications on the market. The declaration on the package generally provides information on the ingredients and the chemical composition. Generally, water storage evaluations and water budget declarations on substrate packages are based on assumptions or are missing. However, accurate substrate hydraulic criteria, parameters and measurement data can improve the evaluation of the hydraulic performance of horticultural substrates in horticulture [3].

The aim of this study was to compare and evaluate the hydraulic properties of some commercially available substrates for horticultural applications. Some important questions were: Do commercially available substrates meet hydraulic requirements (sufficient easily available water and air, high capillarity, low shrinkage, good wettability) for gardening? Are there correlations between the ingredients and basic properties of horticultural substrates with hydraulic properties? Does the package labelling provide conclusions on the hydraulic quality of horticultural substrates? The results of evaluation of a set of horticultural substrates are presented.

2. Experimental Section

2.1. Horticultural Substrates

A set of 36 commercial horticultural substrates (HS) for different horticultural applications was analysed (Table 1). The samples varied in their bog peat and ash content (x), the added ingredients, their price and other properties. Most substrates consisted of 80% or more bog peat (HS No. 1, 2, 4, 5, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32 and 35) with added mineral and/or organic ingredients (garden residual and compost, forest residual, clay, sand, perlite, coir, lime, guano). In some substrates there was much less bog peat (No. 3, 6, 25, 36) and two substrates (33, 34) were peat-free. The Chrysal active substrate package (No. 8) provided no information about the ingredients.

2.2. Hydraulic Criteria

The hydraulic properties were evaluated as an example for plant growth in 20-cm-high containers and for bed cultivation with free drainage. Hydraulic criteria were the easily plant-available water capacity at a tension of 100 hPa (EAW_{100}, growth in container, difference of water content at air capacity and at 100 hPa) and 800 hPa (EAW_{800}, bed cultivation, water content difference between field capacity and water content at 800 hPa), the air (Air) capacity, and the capillary rise. High-quality horticultural soils were designed to provide 24% by vol. or more easily plant-available water. The air capacity (Air) was expected to exceed 10% by vol. [3] to avoid stress due to air limitations. The capillary height calculated for a 5 mm·day^{-1} rate (CR_5) was used as an additional indicator to estimate the flow resistance and the hydraulic suitability and quality of the substrate regarding the easy exchange of water and nutrients in the growing layer. A capillary height of 30 cm was defined as the threshold value. The limiting factors were water repellency effects and shrinkage. With reference to Blanco-Canqui and Lal [4], the water drop penetration time (WDPT, Letey [5]) was not to exceed 5 s to avoid negative effects on water infiltration due to water repellency. Longer wetting times could be an indicator for rewetting limitations and preferential flow [6]. The shrinkage volume of 5% by vol. was not to be exceeded to avoid adverse effects on plant growth and resource management.

2.3. Hydraulic Measurements

The water retention curve and the unsaturated hydraulic conductivity function were measured using the extended evaporation method (EEM) and the HYPROP system from saturation to close to the wilting point [7,8]. If hydraulic information in the dry range is not required, the measurement could be stopped at 100 hPa or at any other tension. These functions were used to calculate the water capacities EAW_{100} and EAW_{800}, to measure the Air capacity and to quantify the CR_5. The shrinkage at 800 hPa was derived from the oven-dried (105 °C) sample. Horticultural substrates with measured oven-dry shrinkage (S_{dry}) of less than 25% by vol. generally provide shrinkage lower than the 5% by vol. at 800 hPa (shrinkage threshold value). The WDPT, as a measure for the rewetting behaviour, was measured after 4 h of free evaporation from the fresh substrate sample.

Table 1. List of commercial horticultural substrates.

HS	Product	Price x	Application y	Ingredients z
1	Falkena	M	P	90% Hh (H4–H8), 10% C
2	Plantop	M	P	Hh (H2–H5), G, F
3	Plantop, for grass	M	F	35% Hh (H2–H8), 30% F, 15% G, 20% L, C, S
4	Falkena, rhododen	M	F	Hh (H3–H9)
5	Falkena, potting soil	M	P	Hh (H3–H8), P, C
6	Bodengold, bio.	M	P/F	40% Hh (H2–H8), 20% F, 40% G, P, C
7	Bodengold, premium	M	P	100% Hh (H2–H5), P, C
8	Chrysal, active soil	H	P	no information
9	Cuxin, balcony plants	H	P	Hh (H3–H7), C, Co
10	Cuxin for turf rolls	H	F	Hh, G, Co
11	Falkena, balcony	M	P/F	Hh (H2–H9)
12	Mecklenburger	kA	F	Hh (H3–H5)
13	Treff_Jiffy Products	kA	F	Hh (H5–H8)
14	Plantop, substrate I	M	P/F	80% Hh (H2–H8), 15% F, 5% G
15	Thomas Phillips	M	P	80% Hh (H3–H7), 15% F, 5% G, S
16	Netto supermarket	M	P	Hh (H3–H8), F, G
17	Blumenrisse	M	P	100% Hh (H2–H8), C
18	Gartenkrone	M	P	80% Hh (H4–H8), F, P, Gu
19	Compo Sana	H	P	96% Hh (H3–H8), P, Gu
20	Floragard	H	P	100% Hh (H2–H8), Gu
21	Fleurelle	M	P	Hh (H2–H6), F, G, Gu
22	Hewita Flor	M	P/F	Hh (H2–H6), G, C, S
23	Grüne Welle bio soil	M	P/F	Hh (H2–H5), G, W
24	Compo Bio.	H	F	Hh (H2–H5, H6–H8), G, Gu, Ca
25	Cuxin, for vegetables	H	F	60% Hh (H3–H5, H5–H7), G, C, L
26	Stender potting soil	M	P	100% Hh (H3–H5, H5–H7), C
27	Frux with natural clay	H	P	Hh, C
28	Euflor, plantahum	H	P/F	Hh (H3–H5), S, C
29	Kuhlmann potting soil	M	F	82% Hh, 10% G, 5.5% S, 2.5% C
30	Grüne Welle	M	P	Hh (H3–H6), C
31	Raiffeisen Gartenkraft	M	P	97% Hh (H3–H8), C, Ca, 0.07% Gu
32	Cuxin, for container	H	P	Hh (H3–H4, H5–H6), Co, C
33	DCM Cuxin, peat-free	H	P	100% Co
34	Neudohum, peat-free	H	P	F, CO, C
35	Uniflor, Schohmaker	M	P	100% Hh
36	Pro-green-BK	kA	P/F	30% Hh, 40% Co, 30% P

x Price: M—medium; H—high; kA—no information; y Recommended use: P—container; F—bed cultivation; P/F—container and bed; z Ingredients: Hh—bog peat; H—degree of decomposition; G—garden residual and compost; F—forest residual; T—clay; S—sand; L—loam; P—perlite; Co—coir; Ca—lime; Gu—guano.

2.4. Statistical Analysis

The statistical analysis aimed to identify predictors for the hydraulic properties of the different substrates. Different approaches were used for metric and nominal candidate predictor variables. In total, 22 predictor variables were investigated. The level of significance was $p < 0.05$. To test for significant relationships between nominal predictor variables and the hydrological properties of the substrates, non-parametric Spearman rank correlation was used to account for the non-Gaussian distribution of the values. Out of all the candidate predictor variables, 19 were nominal variables, and 15 of these were in only two groups. Due to the different numbers of replicates and non-Gaussian bivariate distribution, the non-parametric Mann-Whitney test was used to check for significantly different median values between the respective two groups. The statistical analyses and some of the figures were produced using the R software, version 2.12.0 (R Foundation for Statistical Computing, Vienna, Austria) [9].

3. Results and Discussion

3.1. Hydraulic Properties

Table 2 presents all the relevant hydraulic properties of the substrates under study in detail. The results showed great variability among the substrates. The saturated water content varied between 77.2% and 90% by vol. (an average 84.9% by vol.), and the permanent wilting point reached values between 7.9% and 20.9% by vol. (an average 14.2% by vol.). These values were comparable with slightly decomposed natural peat soils [10] and with values for horticultural substrates [3,11–15]. The EAW_{100} (25.4%–44.1% by vol., average 32.4%) in 20-cm-high containers was much higher than under bed cultivation (18.3%–36.0%, average 23.4%). However, in some cases, substrates with high amounts of easily plant-available water showed limitations for air, shrinkage and/or rewetting. The rewetting was limited in more than 30% of the substrates.

Table 2. Hydraulic properties of the horticultural substrates.

HS No.	Θs	FC	pWP	Air_{p20}	Air_{Bed}	EAW_{p20}	EAW_{Bed}	S_{dry}	CR_5	$WDPT_4$
	% by vol.								cm	s
HS 1	86.2	48.4	11.9	9.4	37.8	32.7	20.0	29.2	24.4	5
HS 2	77.2	43.0	18.1	8.5	34.2	31.2	19.8	19.1	10.1	20
HS 3	78.8	42.2	16.2	8.4	36.6	32.9	19.0	20.2	26.7	12
HS 4	88.8	55.0	10.9	7.9	33.8	30.1	25.3	35.9	47.7	13
HS 5	86.3	47.8	14.4	13.1	38.5	27.9	18.3	25.3	45.7	0.1
HS 6	80.7	46.7	13.5	12.8	34.0	25.4	19.7	22.2	13.1	1
HS 7	87.2	52.1	15.3	10.6	35.2	29.2	23.8	27.1	54.7	0.1
HS 8	88.9	55.2	16.3	9.2	33.8	29.9	25.7	23.6	45.3	0.1
HS 9	90.0	54.6	19.0	6.0	35.4	25.9	27.5	27.2	29.3	0.1
HS 10	87.3	45.0	14.5	12.4	42.4	34.9	21.2	22.1	30.6	0.1
HS 11	84.3	46.7	11.6	6.3	37.6	34.2	19.0	29.8	30.4	32
HS 12	88.3	39.5	18.3	10.7	48.8	44.1	20.8	22.8	40.5	3
HS 13	87.6	47.2	16.8	8.3	40.5	37.2	24.9	24.1	18.3	57
HS 14	80.3	44.8	18.7	8.7	35.5	32.3	20.1	24.1	21.8	17
HS 15	86.2	51.7	13.6	7.5	34.5	32.1	25.2	31.3	29.0	7
HS 16	85.5	44.4	17.1	9.1	41.1	36.9	20.3	23.8	15.9	10
HS 17	87.7	54.3	15.2	10.5	33.4	26.4	26.0	35.2	35.3	1
HS 18	88.1	50.8	13.3	13.5	37.3	27.6	24.5	29.5	52.7	0.1
HS 19	88.3	51.1	7.9	10.9	37.2	30.5	26.0	27.1	36.4	1
HS 20	86.5	48.0	16.7	12.2	38.4	30.5	23.1	27.7	46.4	2
HS 21	89.3	48.7	13.2	13.9	40.6	32.1	23.5	19.1	21.5	1
HS 22	86.6	49.2	16.1	6.0	37.5	37.6	24.7	26.3	29.8	0.1
HS 23	77.9	41.4	11.3	8.0	36.5	33.1	18.4	18.4	37.2	19
HS 24	85.9	58.2	14.2	5.0	27.7	30.5	32.2	23.4	87.9	0.1
HS 25	82.9	44.6	16.7	9.8	38.3	34.3	23.9	24.7	12.7	3
HS 26	84.7	47.5	15.9	8.0	37.2	36.2	26.4	23.4	37.2	32
HS 27	83.6	51.9	11.4	4.2	31.7	34.6	36.0	32.1	79.9	240
HS 28	83.6	44.7	20.9	6.5	38.8	36.9	21.0	27.8	53.4	5
HS 29	81.6	47.4	11.1	6.7	34.3	32.3	24.0	24.9	69.6	7
HS 30	79.3	43.3	11.3	8.0	36.0	32.8	19.9	24.0	57.7	1
HS 31	84.5	50.7	10.4	8.7	33.8	30.0	23.9	28.4	53.0	1
HS 32	83.2	49.4	10.8	6.1	33.8	33.8	27.4	20.6	42.9	62
HS 33	89.0	38.1	9.1	17.0	50.9	38.2	25.1	14.5	76.3	0.1
HS 34	84.1	44.3	10.0	6.0	39.9	25.5	19.6	13.0	17.9	0.1
HS 35	79.9	53.2	15.1	23.9	26.7	25.4	22.7	27.6	26.0	10
HS 36	83.4	40.8	12.3	17.5	42.7	37.7	24.7	8.0	40.1	0.1
MW	84.8	47.8	14.1	9.8	37.0	32.6	23.4	24.5	38.8	15.6

Abbreviations:Θs—saturated water content; FC—field capacity at 60 hPa tension; pWP—permanent wilting point; Air_{p20}—air capacity in a 20-cm-high container; Air_{Bed}—air capacity at free drainage; EAW_{p20}—easily plant-available water in a 20-cm-high container; EAW_{Bed}—easily plant-available water fixed between FC and water content at 800 hPa; S_{dry}—shrinkage volume of the oven-dry sample; CR_5—capillary height of a 5 mm·day^{-1} rate; $WDPT_4$—water drop penetration time after 4 hours' free evaporation; MW—mean value.

3.2. Quality Scores

Taking into account the evaluation scales developed by Schindler and Mueller [16], the suitability of the substrates was evaluated for containers and for a bed (Table 3). The "total" score in Table 3 stands for an average evaluation with no direct link to any special application and crop. We could not find substrates which were evaluated as satisfactory or non-satisfactory for horticultural use. Twenty horticultural substrates (HS: 1, 5, 7, 8, 10, 12, 17, 18, 19, 20, 21, 24, 25, 28, 29, 30, 31, 33, 36) did meet all requirements for a very good hydraulic evaluation for horticultural use in both containers and beds. They provided sufficient easily plant-available water and air, and they were not or not markedly limited by shrinkage and water repellency. Two of them, HS 33 and HS 36, provided the best hydraulic performance of all the substrates under study with a score of 11.5. One noteworthy fact was that HS 33 was peat-free and consisted of 100% coir, while HS 36 was composed of 30% bog peat, 40% coir and 30% perlite. Eight of the substrates (HS: 3, 4, 6, 9, 22, 23, 32, 35) were evaluated as very well-suited or well-suited either for containers or for bed cultivation, and 7 (HS: 2, 11, 13, 14, 15, 16, 35) were evaluated as good for both kinds of cultivation. Only one substrate (HS 27) was of lower hydraulic quality than the others. This substrate was medium- to well-suited. It provided the highest level of easily plant-available water but was strongly affected by shrinkage and water repellency. Furthermore, the air volume after free drainage in 20-cm-high containers was strongly limited, only 4.2% by vol., and was the lowest of all the test substrates.

Table 3. Evaluation of the horticultural substrates.

Sub-Strate	Score_Basic Requirement				Score Limitation			Score		
	Container		Bed							
	EAW_{p20}	Air_{p20}	EAW_{Bed}	Air_{Bed}	CR_5	S_{dry}	$WDPT_4$	Bed	Cont.	Total
PS 1	5	4	4	5	1	1	0	9	9	9
PS 2	5	4	3	5	1	0	2	8	7	7.5
PS 3	5	4	3	5	1	0	1	9	8	8.5
PS 4	5	3	5	5	2	2	1	7	9	8
PS 5	5	5	3	5	2	1	0	11	9	10
PS 6	5	5	3	5	1	0	0	11	9	10
PS 7	5	5	4	5	2	1	0	11	10	10.5
PS 8	5	4	5	5	2	0	0	11	12	11.5
PS 9	5	3	5	5	1	1	0	8	10	9
PS 10	5	5	4	5	2	0	0	12	11	11.5
PS 11	5	3	3	5	2	1	2	7	7	7
PS 12	5	5	4	5	2	0	0	12	11	11.5
PS 13	5	4	5	5	1	0	2	8	9	8.5
PS 14	5	4	4	5	1	0	2	8	8	8
PS 15	5	3	5	5	1	2	1	6	8	7
PS 16	5	4	4	5	1	0	1	9	9	9
PS 17	5	5	5	5	2	2	0	10	10	10
PS 18	5	5	5	5	2	1	0	11	11	11
PS 19	5	5	5	5	2	1	0	11	11	11
PS 20	5	5	4	5	2	1	0	11	10	10.5
PS 21	5	5	4	5	1	0	0	11	10	10.5
PS 22	5	3	5	5	1	1	0	8	10	9
PS 23	5	4	3	5	2	0	2	9	8	8.5
PS 24	5	3	5	5	2	0	0	10	12	11
PS 25	5	4	4	5	1	0	0	10	10	10
PS 26	5	4	5	5	2	0	2	9	10	9.5
PS 27	5	2	5	5	2	2	2	5	8	6.5
PS 28	5	3	4	5	2	1	0	9	10	9.5
PS 29	5	3	5	5	2	0	1	9	11	10
PS 30	5	4	3	5	2	0	0	11	10	10.5
PS 31	5	4	4	5	2	1	0	10	10	10
PS 32	5	3	5	5	2	0	2	8	10	9
PS 33	4	5	5	5	2	0	0	12	11	11.5
PS 34	5	3	3	5	1	0	0	9	9	9
PS 35	5	5	4	5	1	1	1	9	8	8.5
PS 36	4	5	5	5	2	0	0	12	11	11.5

Abbreviations: EAW_{p20}—easily plant-available water in a 20-cm-high container; Air_{p20}—air capacity in a 20-cm-high container; EAW_{Bed}—easily plant-available water fixed between FC and water content at 800 hPa; Air_{Bed}—air capacity at free drainage; CR_5—capillary height of a 5 mm·day^{-1} rate; S_{dry}—shrinkage volume of the oven-dry sample; $WDPT_4$—water drop penetration time after 4 hours' free evaporation; Cont.—container.

3.3. Correlations of Hydraulic Ratings with Basic Properties and Statistical Grouping

For four different ingredients of the substrates, the content was declared on the package. Among these, neither the ash content nor the content of organic residuals was significantly correlated with any of the physical substrate properties studied or with the quality scores. The substrates spanned a wide range from 0 to 100% bog peat material, although most of them contained more than 70%. The bog peat content had a significantly positive effect on the scores (S) for the height of capillary rise (S_B_{CR5}). In addition, it significantly increased two unfavourable properties: the drop infiltration time (WDPT4) and the extent of shrinking during desiccation (S_{dry} and the score S_L_{Sdry}) (Figure 1). No significant effects were found on any of the remaining 11 properties or quality scores.

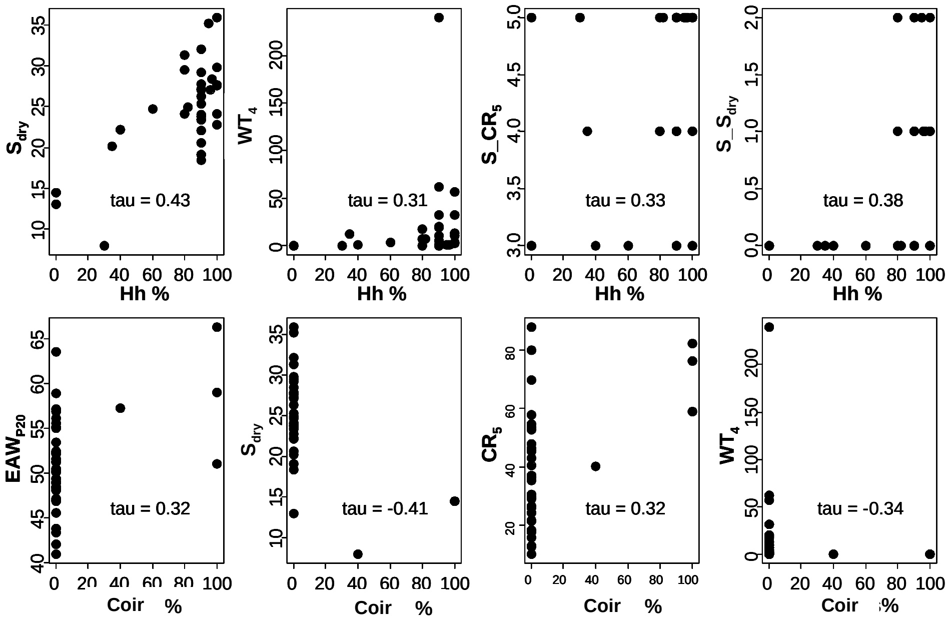

Figure 1. Significant relationships between metric predictor variables and dependent variables.

Only four out of the 32 substrates studied contained coir. Among these, one consisted exclusively of coir. Coir correlated positively with two favourable properties: the height of capillary rise (CR_5) and the easily available water content at a container height of 20 cm (EAW_{p20})—and inversely with two detrimental properties: the extent of shrinking during desiccation (S_{dry}) and the drop infiltration time ($WDPT_4$) (Figure 1).

As there was no quantitative declaration on numerous packages, the effects of mineral ingredients in general, perlite, and organic residuals could only be checked based on their presence or absence.

Mineral ingredients in general decreased the content of easily available water in the bed (EAW_{Bed}) (Figure 2), but did not exhibit any significant effect on any of the remaining properties studied or the quality scores. In contrast, the presence of perlite had significantly positive effects on the mean air content in the case of 20-cm-high containers (Air_{P20}, $S\_B_{Air\ p20}$) and for total scores for suitability in containers ($S\_T_{container}$) and in general (S_T). In addition, perlite increased wettability, indicated by a negative correlation with the infiltration time ($WDPT_4$). The presence of organic residuals had significant and detrimental effects on the height of capillary rise (CR_5, S_CR_5).

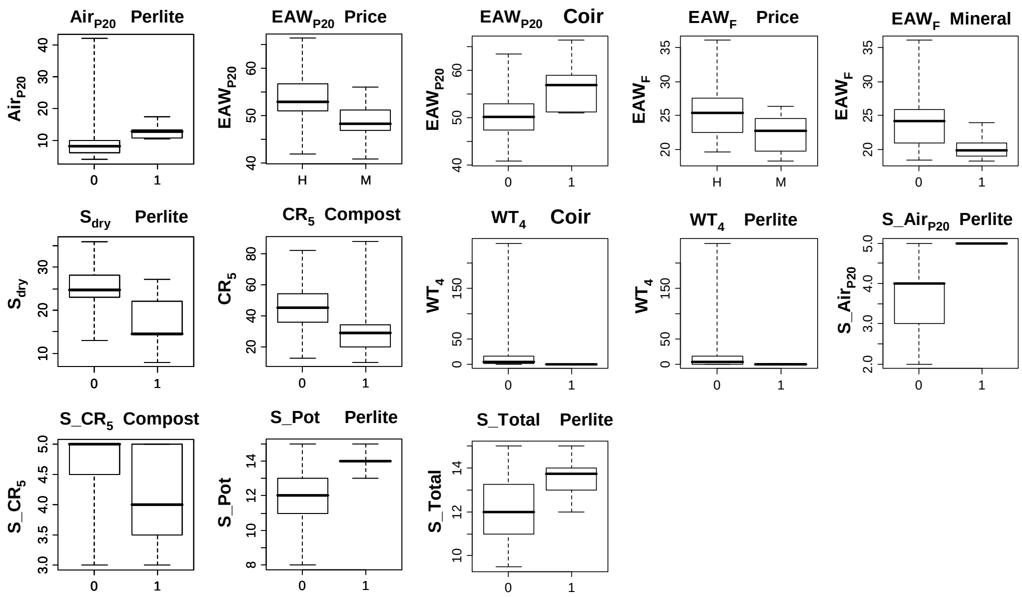

Figure 2. Significant effects of nominal predictor variables on the dependent values (range and quartiles).

The declaration of suitability for different purposes was not significantly correlated with any of the properties studied or the quality scores. High-priced horticultural substrates only differed significantly from less expensive substrates with respect to the content of easily available water both in the bed and in the container (EAW_{p20}, EAW_{Bed}).

Generally, bog peat is the main component of horticultural substrates. However, the best evaluation of the substrate hydraulic suitability in this study revealed substrates composed of bog peat with addition of coir, perlite and organic residuals. Heiskanen's findings [11] agreed with these results, showing the positive impact of perlite on reducing shrinkage and increasing unsaturated hydraulic conductivity in the low tension range. The content of bog peat had a significantly positive effect on the height of capillary rise. In addition, it significantly increased two unfavourable properties: the drop infiltration time and the extent of shrinking during desiccation. The presence of organic residuals had significant and detrimental effects on the height of capillary rise. Coir correlated positively with two favourable properties: height of capillary rise and easily available water content with a container height of 20 cm; and inversely with two detrimental properties: extent of shrinking during desiccation and drop infiltration time.

Results found by Pittenger [17] revealed the importance of bark, bog peat and vermiculite for high-quality substrate mixtures. The results of this study showed that mineral ingredients in general decreased the content of easily available water but did not exhibit any significant effect on the remaining properties studied or the quality scores. However, the risk of a lack of air can be increased by adding clay. In contrast, the presence of perlite had significantly positive effects on air content in the case of 20-cm-high containers. These results fit with the findings by Regand et al. [18], Özkaynak and Samanci [19], and Fazeli et al. [20], who concluded that the best mixture for plantlet growth was peat moss, perlite or sand, respectively. In addition, perlite increased wettability, indicated by a negative correlation with infiltration time. These findings agree with results by Raviv and Lieth [3] and Al Naddafa [14].

4. Conclusions

This study provides some initial information about the hydraulic properties and performance of some commercial substrates for horticulture. This kind of information is intended to expand our knowledge of substrate hydraulic properties and help in the evaluation of substrate suitability in horticulture. The hydraulic performance of totally peat-free substrates was not worse than those containing peat. However, other substrates and substrate mixtures, with bog peat from different parts of the world (Canada, Estonia, Finland and other), and with various alternative ingredients, should be analysed. The proposed method provides a simple and practicable solution.

We found major differences between the tested substrates and substrate compositions. The hydraulic values differed markedly between production in containers versus in beds with free drainage. Lack of air, especially in shallow containers, and water repellency were the relevant deficits. Of the 36 horticultural substrates under study, the great majority earned a good to very good hydraulic rating.

Buyers of horticultural substrates cannot make any assumptions based on the hydraulic properties of the particular product they have bought. However, from the test results above, the probability is very high that the product will perform well or very well hydraulically if the substrate is largely free of clay.

A comprehensive evaluation of the eligibility of horticultural substrates in horticulture, however, requires not only hydraulic measurements but also production studies and an assessment of their chemical, biological and technological suitability. These will be topics for future studies.

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References

1. Yogev, A.; Raviv, M.; Hadar, Y. Plant-waste based compost suppressive to deseases caused to pathogenic Fusarium oxysporum. *Eur. J. Plant Pathol.* **2006**, *116*, 267–278. [CrossRef]
2. Verdonck, O. Status of soilless culture in Europe. *Acta Hortic.* **2007**, *742*, 35–39. [CrossRef]
3. Raviv, M.; Lieth, J.H. *Soilless Culture*; Elsevier Publications: London, UK, 2008; p. 608.
4. Blanco-Canqui, H.; Lal, R. Extent of soil water repellency under long-term no-till soils. *Geoderma* **2009**, *149*, 171–180. [CrossRef]
5. Letey, J. Measurement of contact angle, water drop penetration time, and critical surface tension. In *Water-Repellent Soils*; DeBano, L.F., Letey, J., Eds.; University of California: Berkeley, CA, USA, 1968; pp. 43–47.
6. 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]
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. Schindler, U.; Mueller, L.; Eulenstein, F. Hydraulic performance of horticultural substrates—1. Method for measuring the hydraulic quality indicators. In Proceedings of the International Symposium on Quality Management of Organic Horticultural Produce, Ubon Ratchathani, Thailand, 7–9 December 2015.
9. R Development Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2010.
10. Wösten, J.H.M.; Lilly, A.; Nemes, A.; Le Bas, C. Development and use of a database of hydraulic properties of European soils. *Geoderma* **1999**, *90*, 169–185. [CrossRef]
11. 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]
12. Richards, D.; Lane, M.; Beardsell, D.V. The influence of particle size distribution in pinebark, sand, brown coal potting mixes on water supply aeration and plant growth. *Sci. Hortic.* **1986**, *29*, 1–14. [CrossRef]
13. Nowak, J.S.; Strojny, Z. Changes in physical properties of peat-based substrates during cultivation period of gerbera. *Acta Hortic.* **2004**, *644*, 319–323. [CrossRef]
14. Al Naddafa, O.; Livieratos, I.; Stamatakisa, A.; Tsirogiannisb, I.; Gizasb, G.; Savvasc, D. Hydraulic characteristics of composted pig manure, perlite, and mixtures of them, and their impact on cucumber grown on bags. *Sci. Hortic.* **2011**, *129*, 135–141. [CrossRef]

15. Caron, J.; Pepin, S.; Periard, Y. Physics of growing media in a green future. International Symposium on Growing Media and Soilless Cultivation. *Acta Hortic.* **2014**, *1034*, 309–317. [CrossRef]
16. Schindler, U.; Mueller, L. Hydraulic performance of horticultural substrates—2. Development of an evaluation framework. In Proceedings of the International Symposium on Quality Management of Organic Horticultural Produce, Ubon Ratchathani, Thailand, 7–9 December 2015.
17. Pittenger, D.R. Potting soil label information is inadequate. *Calif. Agric.* **1986**, *40*, 6–8.
18. Regand, R.V.; Machado, S.; Alam, M.; Ali, A. Greenhouse production of potato (*Solanum tuberosum* cv. *Desiree*) seed tubers using in-vitro plantlets and rooted cutting in large propagation beds. *Potato Res.* **1995**, *38*, 61–68.
19. Özkaynak, E.; Samanci, B. Yield and yield components of greenhouse, field and seed bed grown potato (*Solanum tuberosum* L.) plantlets. *Akdeniz Univ. Ziraat Fak. Derg.* **2005**, *18*, 125–129.
20. Fazeli Sabzevar, R.; Mirabdulagh, M.; Zarghami, R.; Pakdaman, B. Mini-tuber production as affected by planting bed composition and node position in tissue cultured plantlet in two potato cultivars. *Int. J. Agric. Biol.* **2007**, *9*, 416–418.