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Hydrological Behavior of Peat- and Coir-Based Substrates and Their Effect on Begonia Growth

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Received: 15 March 2018; Accepted: 29 May 2018; Published: 2 June 2018

Abstract: The physical–hydraulic properties of eight substrate mixtures based on sphagnum peat and coir were determined and their effect on the growth of *Begonia* x*elatior* was studied. The particle size distribution, water retention curve, saturated hydraulic conductivity, and pore size distribution of the substrates were determined. All substrates exhibited high total porosity, satisfactory water retention capacity, and high saturated hydraulic conductivity. Increasing the percentage of perlite in the mixtures contributed to the reduction of water retention capacity and the increase of large pores. Unsaturated hydraulic conductivity estimated by the Mualem–van Genuchten model showed a sharp decrease within a range of water pressure heads (0 to −50 cm) observed between two successive irrigations. To assess aeration and water retention capacity, total porosity; airspace; and easily, and nonavailable water, as well as the bulk density of the substrates, were determined and concomitantly compared with the "ideal substrates" determined by De Boodt and Verdonck. The comparative results showed that substrate porosity alone is not efficient to create ideal plant growth conditions, but dynamic parameters are also needed. Plants grown in a substrate classified as "nonideal" showed significantly greater growth than the plants grown in most of the other substrates studied.

Keywords: water retention curve; pore size distribution; particle size distribution; horticultural substrates; plant growth

1. Introduction

Soilless growing substrates used in greenhouse, container, and green-roof production systems consist of either organic materials or mixtures of organic and inorganic materials. Suitable attributes of the materials used in these substrates for horticultural use are low cost and physical properties supporting adequate aeration and water retention for optimal plant growth.

Sphagnum peat is a widely used substrate for ornamental plant production [1–4]. Altogether, economics, availability of new materials, and peat environmental awareness led to the interest in new substrates [5]. Research has been heavily focused on the use of industrial, municipal, or agricultural wastes (e.g., [6,7]), but some of these either are not produced in sufficient quantities and/or may contain undesirable materials or properties (chemical and physical). The most promising alternative media are coir, bark, wood fibers, and composts [8]. Also, there are other products that are considered alternative substrates to peat, such as different mixtures based on biochar or by-products of the agri-food industry [9].

During the last two decades, coconut coir has become a widely accepted peat substitute, showing growth results comparable to sphagnum peat (e.g., [10–14]).

Coconut coir is an organic by-product derived from the mesocarp tissue or husk fiber treatment of the coconut (*Cocos nucifera*) fruit. The long fibers are used for industrial purposes, and the remaining materials, consisting of short fibers and dust, undergo aerobic composting. After composting, the stable material is dehydrated and compressed into a compact form (bricks) for easy transportation. With the addition of water, coir expands to 5 to 9 times its compressed volume.

Coir can serve either as a stand-alone growing medium or as an ingredient in a mix for use in horticulture. Coir is used primarily as a peat alternative [10,11]. The physical properties of coir and peat have been studied by many researchers [14–23].

Substrates such as peat and coir offer many advantages, such as low bulk density, being pathogen- and weed seed-free, high water retention capacity, and easy root penetration. The primary disadvantages of peat and coir are poor aeration and low pressure heads due to a low percentage of large particles. This creates a problem in the water–air balance and gas exchange under different watering regimes [1,3,14,24]. To mitigate this disadvantage in pure substrates, various materials characterized by large particle sizes are added, with perlite being the most popular one used [2,14,20,25]. The addition of coarse perlite to peat improves aeration [2,14,20,25–28].

However, the addition and mixture of different materials raises questions about the ratios of the substrate's mixture components to create a high-quality substrate for optimum plant growth.

Standards for substrates were developed by De Boodt and Verdonck [24], determining appropriate physical values, such as total porosity, airspace, and water capacity for optimum plant growth in containers and in bed cultivation. De Boodt and Verdonck [24] recommend a limit of water availability in a water pressure range of -10 to -100 cm. This limit was later confirmed by other researchers [29,30]. These standards have been implemented and used commercially at a large scale [31–33] and still form the basis for manufacturing growth substrates [34]. However, less attention was paid to dynamic parameters and processes such as water use and gas diffusivity [34]. In this direction, we try to point out the necessity of using, also, dynamic parameters in substrate evaluation.

This paper presents a study of the physical–hydraulic characteristics of eight substrate mixes based on peat and coir and assessment of their effect on the growth of *Begonia* x*elatior*. The main objective was to determine the hydraulic characteristics of these substrates, widely used in floriculture, and the secondary, to evaluate them with the properties identified by De Boodt and Verdonck [24] in making the "ideal substrates". Also, it is investigated whether it is sufficient to assess the suitability of the substrates based only on their static hydraulic characteristics.

2. Materials and Methods

2.1. Soilless Growing Substrates

Eight substrate mixtures based on peat or coir were selected for use in begonia cultivation (Table 1). The substrates studied were (on a volume basis): (i) 100% sphagnum peat (Ps) (Lithuanian peat, Vilnius, Lithuania); (ii) 75% sphagnum peat and 25% perlite (Ps_{75}:P_{25}); (iii) 50% sphagnum peat and 50% perlite (Ps_{50}:P_{50}); (iv) 100% coir (C), a byproduct of coconut husk fiber treatment in compressed form with dimensions 20 cm $\times$ 10 cm $\times$ 5 cm (van der Knaap, Wateringen, The Netherlands); (v) 75% coir and 25% perlite (C_{75}:P_{25}); (vi) 50% coir and 50% perlite (C_{50}:P_{50}); and two commercially available prefortified mixes with macro- and microelements, widely used by professional horticulture producers in Greece, that are constituted of: (vii) 60% sphagnum peat, 30% black peat (peat humus which is highly decomposed organic material that accumulates in the lower levels of peat bogs and has a dark color), and 10% perlite (Ps_{60}:Pb_{30}:P_{10}); and (viii) 70% Arbutus soil (mixture of soil, decomposed leaf litter, and humus of *Arbutus unedo* and *Arbutus andrachne*), 24% sphagnum peat, and 6% perlite (A_{70}:Ps_{24}:P_6). The pH of all substrates was adjusted to 5.5–6.0 with the addition of dolomite limestone. The amounts applied were 5 kg$\cdot$m^{-3} substrate for Ps, Ps_{75}:P_{25}, and Ps_{50}:P_{50} and 1.5 kg$\cdot$m^{-3} substrate for Ps_{60}:Pb_{30}:P_{10}. The initial chemical characteristics of all substrates used are given in Table 2. All substrates present low electrical conductivity values (Table 2).

Table 1. Composition on a volume basis of peat- and coir-based substrates used.

Substrate	Sphagnum Peat	Black Peat	Coir	Arbutus Soil	Perlite
	(% *v*/*v*)				
Ps	100	-	-	-	-
Ps_{75}:P_{25}	75	-	-	-	25
Ps_{50}:P_{50}	50	-	-	-	50
C	-	-	100	-	-
C_{75}:P_{25}	-	-	75	-	25
C_{50}:P_{50}	-	-	50	-	50
Ps_{60}:Pb_{30}:P_{10}	60	30	-	-	10
A_{70}:Ps_{24}:P_6	24	-	-	70	6

Table 2. Initial chemical characteristics of substrates.

Substrate	EC [1]	Mg	Ca	K	Na	P	N	Fe	Zn	Mn	Cu
	($mS \cdot cm^{-1}$)	(%)						($\mu g \cdot g^{-1}$)			
Ps	0.25bc [2]	0.032a	0.22a	0.015a	0.028a	0.052a	0.55b	22.8a	24.8a	15.7a	4.4a
Ps_{75}:P_{25}	0.16b	0.037a	0.49a	0.039a	0.070b	0.060a	0.48b	32.8a	26.1a	17.2a	6.9a
Ps_{50}:P_{50}	0.05a	0.032a	0.58a	0.026a	0.090bc	0.065a	0.32ab	30.7a	30.3a	19.8a	10.8a
C	0.50d	0.098c	0.29a	0.625d	0.148c	0.040a	0.43b	38.0a	32.6a	35.4b	9.1a
C_{75}:P_{25}	0.30c	0.073b	0.30a	0.300c	0.150c	0.061a	0.36ab	55.2ab	30.1a	41.1b	6.3a
C_{50}:P_{50}	0.20b	0.065b	0.26a	0.350c	0.178c	0.064a	0.23a	71.4b	27.7a	38.7b	5.7a
Ps_{60}:Pb_{30}:P_{10}	0.64e	0.070b	1.63c	0.165b	0.046ab	0.081b	1.07c	56.0ab	33.6a	41.9b	19.2b
A_{70}:Ps_{24}:P_6	0.32c	0.109c	1.20b	0.120b	0.076b	0.091b	1.20c	225.0c	60.3b	46.8b	9.2a

[1] EC: Electrical conductivity values in 1:2 substrate/water extract; [2] columns not followed by the same letter are significant (Tukey–Kramer, at $p = 0.05$; $n = 3$).

2.2. Plant Materials and Cultivation Treatments

Uniform begonia plants (*Begonia* x*elatior*, "The President") supplied by a local nursery were individually planted into 4938 cm^3 pots (height 19.9 cm, base diameter 16.4 cm, and top diameter 19.3 cm) with useful substrate volume 3947 cm^3 (height 16.3 cm, base diameter 16.4 cm and top diameter 18.7 cm). The required amount of each substrate was calculated by multiplying the volume of the substrate and its bulk density, taking into account the initial moisture of the substrate. All pots were packed in the same way as to receive the same substrate volume. Plants were placed in a glass greenhouse at the Agricultural University of Athens (Athens, Greece) and were arranged in a randomized complete block design with 10 replications. Throughout the experiment, the daytime temperature ranged between 20–35 °C and at night-time was approximately 12 °C; the humidity during the daytime ranged between 30%–60% and at night-time was 90%.

The irrigation was initiated manually through an automated irrigation system which consists of an eight-station controller (GreenKeeper 212, TORO, Bloomington, MN, USA), with eight valves and eight corresponding pressure regulators and PE pipelines to connect the water supply through the controller to the two drippers positioned opposite each other at the surface of each pot at a water flow rate of 2 $L \cdot h^{-1}$. Tensiometer readings were taken each morning throughout the study. Each pot was irrigated with 350 cm^3 of water when the mean tensiometer pressure head reached −50 cm, because it sets the lower limit of easily available water as defined by De Boodt and Verdonck [24]. The amount of irrigation water was enough to barely leach from the bottom of the pot. The values of water tension were measured using the tensiometers as presented by [16], positioned randomly in three pots for each substrate.

Therefore, all plants received the same cultivation procedures (i.e., applications of fertilizer, fungicide, etc.). A soluble 20N/8.7P/16.6K fertilizer at 136 $mg \cdot L^{-1}$ N, fortified with micronutrients (Rosso, ALFA Agricultural Supplies S.A., Athens, Greece), was used at each irrigation event for all plants throughout the duration of the experiment.

2.3. Physical–Hydraulic Properties of Growing Substrates

The following physical–hydraulic properties of the substrates studied were determined:

- Water retention curve measurements were performed on a tension plate apparatus in a Haines-type assembly [35], with an air-entry value of −190 cm of a water column (three samples of each substrate were used). Substrate-sample size approximated the pot diameter used in the experiment; that is, about 3 cm in height and 18.4 cm in diameter.
- The water content at 15,000 cm pressure head was determined using a high-range membrane method [36].
- The saturated hydraulic conductivity, K_s, was determined using the constant-head method [37].
- Pore size distribution was obtained from the retention curves by plotting their slopes as functions of the pressure potential [38].
- The bulk density of each substrate sample was determined for the volume obtained immediately after the last measurement of the water retention curve and drying in an oven for 48 h at 105 °C.
- Screen analysis was performed to determine the particle distribution of the substrates. Three air-dried samples, 100 g mass each, from each substrate used for the plant experiment were placed in the top sieve of a column of sieves of 0.068, 0.125, 0.25, 0.50, 1.00, 2.00, 4.00, and 8.00 mm screen mesh sizes according to decreasing aperture and rested on a sieve shaker for 5 min at 30 shakes per minute.
- Oxygen concentrations of substrates were determined along the depth of the pots using a portable gas analyzer (multi-gas analyzer LMSx, Eijkelkamp, Giesbeek, The Netherlands). Air samples along the depth of the pots were extracted via the perforated chambers into acrylic tubes as presented by Londra et al. [14]. The oxygen-measuring devices were positioned randomly in three pots for each substrate, and O_2 concentrations were measured at 5, 10, and 15 cm height from the base of the pot. The measurements were made before each irrigation event.

2.4. Calculation of the Hydraulic Properties by the Closed-Form Hydraulic Model

The RETC (RETention Curve) program [39], was used to calculate the fitting hydraulic parameters of the popular Mualem–van Genuchten [40,41] model on the experimental water retention data.

Van Genuchten [41] described the water retention curve as

$$\theta(H) = (\theta_s - \theta_r)\left(\frac{1}{1 + (\alpha|H|)^n}\right)^m + \theta_r \tag{1}$$

where θ is the soil water content (cm^3·cm^{-3}); the subscripts s and r indicate saturated and residual values of water content, respectively; H is the water pressure head (cm); and α (cm^{-1}), m (−), and n (−) are curve-fitting parameters: $m = 1 - 1/n$ and $0 < m < 1$.

Combining Equation (1) with the model developed by Mualem [40], the hydraulic conductivity in relation to water content, *K(θ)*, or pressure head, *K(H)*, can be calculated as

$$K(\theta) = K_s\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{0.5}\left\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/m}\right]^m\right\}^2 \tag{2}$$

$$K(H) = K_s\frac{\left[1 - (aH)^{n-1}\left[1 + (aH)^n\right]^{-m}\right]^2}{\left[1 + (aH)^n\right]^{\frac{m}{2}}} \tag{3}$$

The model fitting parameters described above were evaluated by the RETC program using the measured water retention and saturated hydraulic conductivity data. In the parameter optimization process to fit the water retention function, the unknown parameters of the Mualem–van Genuchten model were α, n, and θ_r.

2.5. Plant Growth

Plants were harvested at the end of the cultivation period (after 16 weeks) and divided at soil level into shoot and root. The harvested roots were carefully washed clean from the substrate. Fresh weight of shoot and root samples were determined. Subsequently, samples were dried at 70 °C for 48 h and their dry weights determined. The percent growth increase was calculated as the ratio of the difference between the total dry weight at the end (n = 10) and start of the experiment (n = 10) by the total dry weight at the end of the experiment. As all plants at the beginning of the experiment were uniform in size, the calculated dry weights were considered the same for all treatments.

Leaf samples for nutrient analysis were collected at the end of the experiment and were dried at 70 °C for 48 h. Dried leaf samples were ground in a grinding mill to pass a 0.84 mm (20-mesh) screen. The ground samples were subjected to a wet digestion procedure (HNO_3 and 30% H_2O_2) for nutrient analysis [42]. N concentration was determined by Kjeldahl digestion (Velp Scientifica, UDK 132, Via Stazione, Italy). K and Na concentrations were determined by flame photometer (Corning 410 model, Sherwood Scientific, Cambridge, UK), and all the other nutrients were measured using the atomic absorption spectrophotometer (Spectr AA- 20 model, Varian, Sydney, Australia).

2.6. Experimental Design and Statistical Analysis

The experiment was a randomized complete block design with eight treatments (substrates) and ten replications (ten plants per substrate). The analysis of variance of the experimental data was performed using JMP (SAS Inst., Cary, NC, USA) statistical software, and treatment means were compared using Tukey–Kramer's test at a probability level p = 0.05.

3. Results and Discussion

3.1. Physical–Hydraulic Properties of Growing Substrates

To assess the water retention capacity of the substrates studied, a comparative presentation of water retention curves is given in Figure 1a–c.

The addition of perlite into peat and coir decreases the total porosity (water content at saturation) and water retention capacity of the peat–perlite (Figure 1a) and coir–perlite (Figure 1b) mixtures compared to the pure substrates. The decrease was higher in mixtures with higher percentages of perlite. In the case of the two commercial substrates, the comparison showed that Ps_{60}:Pb_{30}:P_{10} has a greater total porosity and water retention capacity than A_{70}:Ps_{24}:P_6 (Figure 1c). The knowledge gained from the determination of the substrates' water retention curves plays a prime role in proper irrigation management.

In Table 3, the Mualem–van Genuchten model fitting parameters α, n, and θ_r, as well as the experimental values θ_s for all substrates examined, are given. As shown in Figure 1, it is apparent that there is a very good agreement of the results between the experimental and predicted values of $\theta(H)$, indicating that the corresponding soil hydraulic parameters listed in Table 3 provide an adequate description of the $\theta(H)$ relationship with a coefficient of determination $R^2 \geq 0.993$ for all substrates.

Differentiating the water retention curve ($d\theta/dH$ at each pressure head H) of all substrates studied (Figure 1a–c), the pore size distribution can be revealed [38,43] and is presented comparatively in Figure 2 as a relationship between $d\theta/dH$ and equivalent pore diameter. As shown, generally, A_{70}:Ps_{24}:P_6 and coir–perlite mixtures (C, C_{75}:P_{25}, C_{50}:P_{50}) have larger macropores (equivalent pore diameter >75 μm), followed by Ps_{60}:Pb_{30}:P_{10} and then peat–perlite mixtures. With regard to the peat–perlite mixtures (Ps, Ps_{75}:P_{25}, Ps_{50}:P_{50}), the addition of perlite increased the size of large pores, especially those associated with the water tension of −5 cm. Pore size increased as the percentage of perlite in the mixture increased. The same was observed in the case of coir–perlite mixtures. On the other hand, Ps_{60}:Pb_{30}:P_{10} and peat–perlite mixtures have larger mesopores (equivalent pore diameter 30–75 μm) than A_{70}:Ps_{24}:P_6 and coir–perlite mixtures. Finally, all substrates analyzed have the same micropores (equivalent pore diameter 5–30 μm).

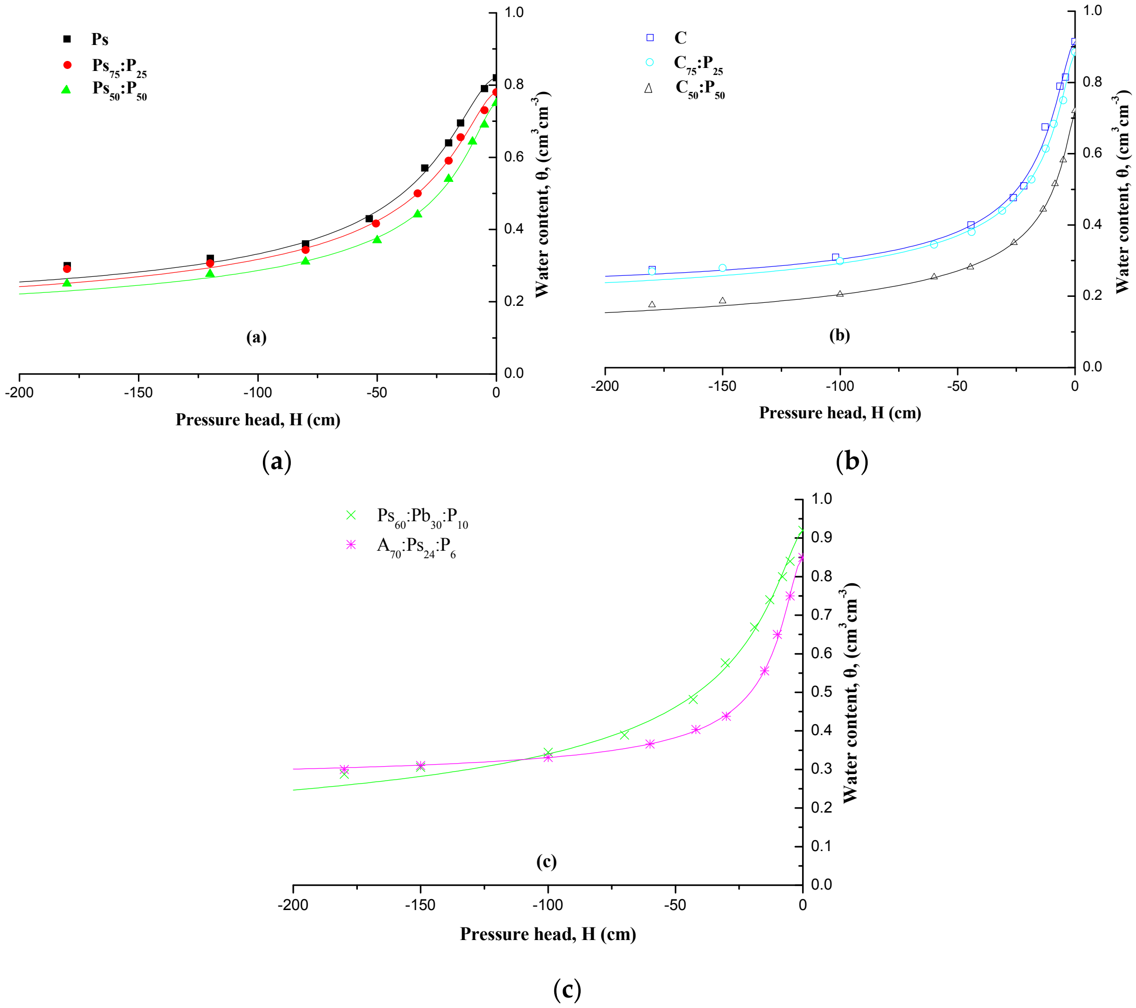

Figure 1. Experimental water retention data (symbols) and predicted curves (lines) obtained by the Mualem–van Genuchten model using the RETC program for the substrates: (**a**) 100% sphagnum peat (Ps); 75% sphagnum peat and 25% perlite (Ps_{75}:P_{25}); 50% sphagnum peat and 50% perlite (Ps_{50}:P_{50}); (**b**) 100% coir (C); 75% coir and 25% perlite (C_{75}:P_{25}); 50% coir and 50% perlite (C_{50}:P_{50}); (**c**) 60% sphagnum peat, 30% black peat, and 10% perlite (Ps_{60}:Pb_{30}:P_{10}); and 70% Arbutus soil, 24% sphagnum peat, and 6% perlite (A_{70}:Ps_{24}:P_6). Values are the means of three replications (*n* = 3).

Table 3. The Mualem–van Genuchten model fitting parameters α, n, θ_r and measured values of θ_s for the substrates.

Substrate	α (cm^{-1})	n (−)	θ_r ($cm^3 \cdot cm^{-3}$)	θ_s ($cm^3 \cdot cm^{-3}$)	R^2
Ps	0.050	1.770	0.140	0.820	0.999
Ps_{75}:P_{25}	0.058	1.634	0.099	0.780	0.997
Ps_{50}:P_{50}	0.076	1.587	0.088	0.75	0.998
C	0.117	1.725	0.182	0.915	0.993
C_{75}:P_{25}	0.145	1.558	0.121	0.885	0.998
C_{50}:P_{50}	0.204	1.416	0.0	0.720	0.999
Ps_{60}:Pb_{30}:P_{10}	0.077	1.479	0.0	0.920	0.998
A_{70}:Ps_{24}:P_6	0.135	1.822	0.262	0.850	0.999

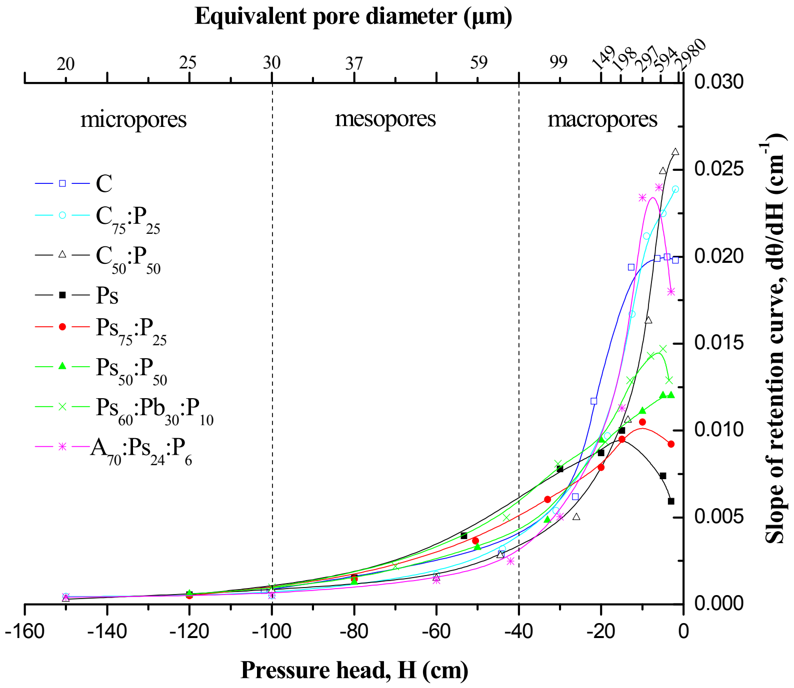

Figure 2. Pore size distribution of the substrates.

With regard to particle size distribution (Figure 3), in the case of the peat–perlite mixtures (Ps, Ps_{75}:P_{25}, Ps_{50}:P_{50}), the addition of perlite decreased the percentage of particle sizes greater than 4 mm and less than 1 mm and increased the percentage of particle sizes between 4 and 1 mm. The same was observed in the case of the coir–perlite mixtures, with the exception of particles greater than 4 mm, where the percentage of these particles increased slightly with the addition of perlite in pure coir. Comparison between peat–perlite and coir–perlite mixtures showed that the latter was characterized by a lower percentage of particle sizes greater than 4 mm and a higher percentage of particle sizes less than 1 mm. In the case of prefortified substrates, Ps_{60}:Pb_{30}:P_{10} was characterized by a lower percentage of particle sizes greater than 1 mm and a higher percentage of particle sizes less than 1 mm compared to A_{70}:Ps_{24}:P_6. It is worth noting that Ps_{60}:Pb_{30}:P_{10} was characterized by the highest percentage of particle sizes less than 1 mm (≈77%) compared to all the other substrates studied. The abovementioned variation of the substrate particle sizes led to differences in various physical properties of the substrates. Large differences in particle size can result in the migration of fine particles into the spaces between larger fragments, resulting in reduced air-filled porosity, increased volumetric water content at specified pressures, and increased bulk density [28].

To evaluate the results received from the water retention curves and both the pore size and particle size distributions, Table 4 was created. In Table 4, the terms introduced by De Boodt and Verdonck [24] are used to characterize the water retention capacity and aeration of substrates in a range of water tensions between 0 (saturation) and −15,000 cm (permanent wilting point). Furthermore, in the same table, the bulk density values of all the substrates studied are shown. In accordance to Table 4, the total porosity, easily available water, water buffering capacity, difficult available water, and nonavailable water were decreased in peat–perlite and coir–perlite mixtures compared to pure peat and coir, respectively. These differences were significant mainly in the case of 50% perlite percentage. On the other hand, as anticipated, substrate air space increased along with increasing the percentage of perlite in mixtures. In the case of the commercial substrates, Ps_{60}:Pb_{30}:P_{10} had significantly greater values of total porosity, easily available water, water buffering capacity, and difficult available water, and a lower value of air space than A_{70}:Ps_{24}:P_6.

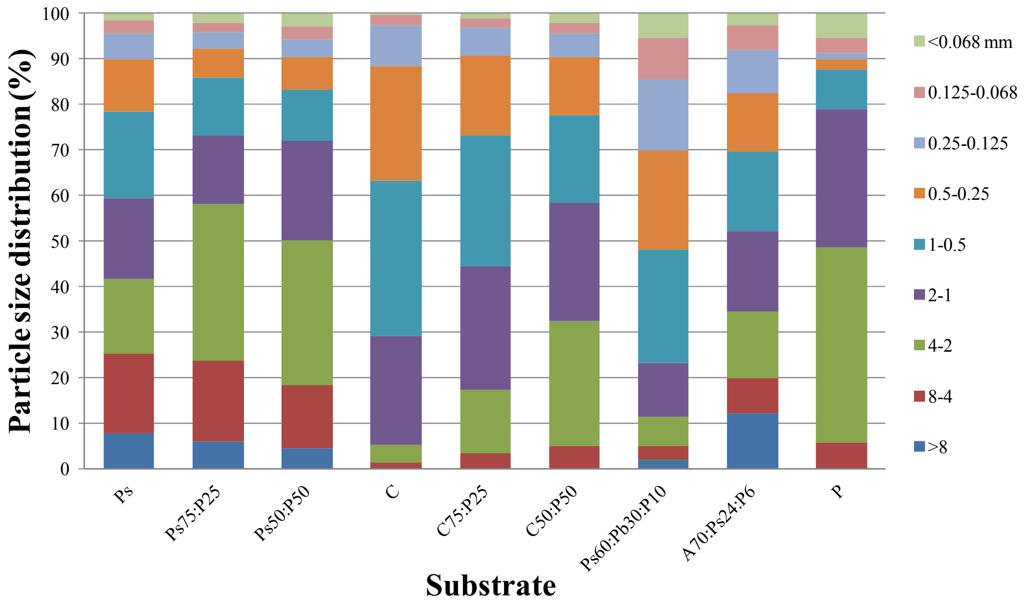

Figure 3. Particle size distribution of the substrates. Values are the means of three replications (*n* = 3).

In Table 4, the corresponding values of "ideal substrates" as identified by De Boodt and Verdonck [24], and which have been implemented and used commercially at a large scale [31–33], are indicated. According to the concept of "ideal substrates", water retention curves below this zone have rapid water release and low water holding capacity, while those above it have less air space and greater water holding capacity. The only substrate to meet this zone for the full range of water tension is A_{70}:Ps_{24}:P_6, as represented in Figure 4, followed by the substrates C_{75}:P_{25} and Ps_{50}:P_{50}. The rest of the substrates have a remarkable portion of their water retention curve falling either below (e.g., C_{50}:P_{50}) or above this zone (e.g., Ps, Ps_{75}:P_{25}, C, C_{50}:P_{50}, Ps_{60}:Pb_{30}:P_{10}).

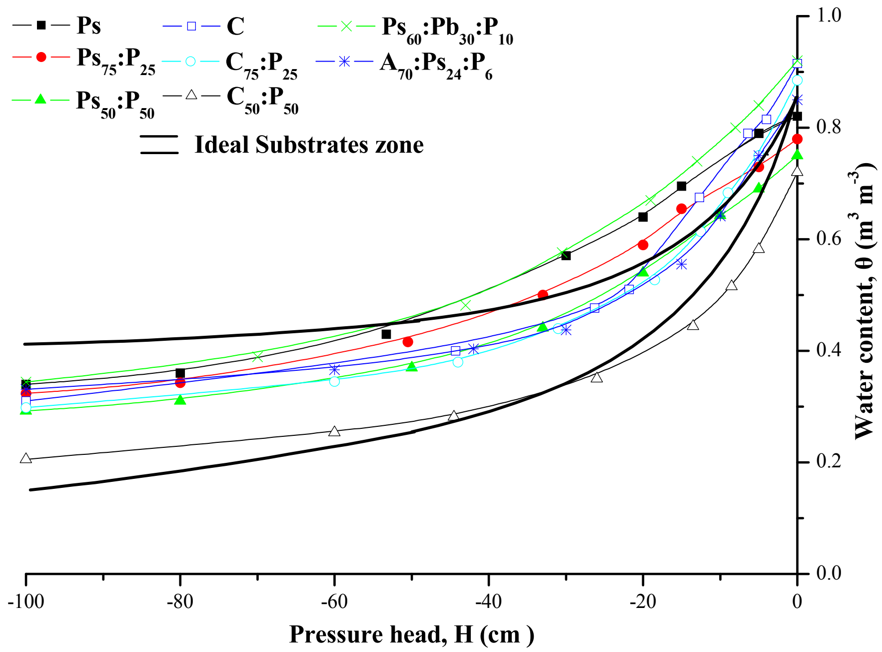

Figure 4. Comparative presentation of measured water retention curves for the substrates and the "ideal substrates zone" identified by De Boodt and Verdonck [24].

In Table 5, the measured values of water content and hydraulic conductivity at saturation (*H* = 0 cm), as well as the predicted ones by the Mualem–van Genuchten model at water pressure heads (*H* = −10, −50, −100 cm) within the range of easily available water and water buffering capacity, as introduced by De Boodt and Verdonck, are presented. As shown, a sharp decrease of the unsaturated hydraulic conductivity was observed within this range of water pressure heads (0 to −100 cm). Similar results have also been reported by other researchers (e.g., [20,44,45]). Comparing the unsaturated hydraulic conductivity values of the substrates A_{70}:Ps_{24}:P_6, C_{75}:P_{25}, and Ps_{50}:P_{50} characterized as "ideal" (Figure 4), it is apparent that remarkable differences exist among them (Table 5). During plant growth in this study, the pressure heads varied from −10 to −50 cm between two successive irrigations (range of easily available water). For this range of pressure heads, the hydraulic conductivity of A_{70}:Ps_{24}:P_6 is decreased by approximately three orders of magnitude, whereas in the rest of the substrates, it is decreased by approximately two orders of magnitude. Specifically, *K* values ranged from 5.5×10^{-1} to 2.4×10^{-4} cm·min^{-1}, with the smallest ones observed for the substrates C_{50}:P_{50} and A_{70}:Ps_{24}:P_6 (Table 5).

The knowledge of both *K*(*H*) and *θ(H)*, is of vital importance mainly in greenhouse cultures and would contribute to alleviating water stress conditions and improving the quality of substrates. Nevertheless, we should bear in mind that in some cases, the predicted *K*(*H*) values using the water retention curve data and the saturated hydraulic conductivity may deviate significantly from the actual *K*(*H*) values [46–50].

In general, during plant growth, the O_2 concentration of the substrates studied was greater than 20.6%. However, there were no significant differences among the substrates nor along the depth of the substrates (data not shown).

Table 4. Physical properties of the substrates. Values are the means of three replications (n = 3).

Substrate	Total Porosity [1] (%)	Airspace [2] (%)	Easily Available Water [3] (%)	Water Buffering Capacity [4] (%)	Difficult Available Water [5] (%)	Nonavailable Water [6] (%)	Solids (%)	Bulk Density ($g \cdot cm^{-3}$)
Ps	82.00d [8]	7.75e	30.03b	10.42a	20.71b	13.09b	18.00d	0.081d
Ps_{75}:P_{25}	78.00e	10.00d	26.40c	9.40ab	19.90b	12.30b	22.00c	0.100bc
Ps_{50}:P_{50}	75.00f	10.70d	27.30c	8.05b	17.15c	11.80c	25.00b	0.116b
C	91.50a	20.07b	32.09ab	7.85bc	18.49bc	13.00b	8.50g	0.089cd
C_{75}:P_{25}	88.50b	20.92b	30.88b	6.64c	17.06c	13.00b	11.50f	0.093c
C_{50}:P_{50}	72.00g	23.00a	22.00d	6.30cd	8.70d	12.00bc	28.00a	0.094c
Ps_{60}:Pb_{30}:P_{10}	92.00a	13.50c	33.20a	10.90a	24.40a	10.00c	8.00g	0.103bd
A_{70}:Ps_{24}:P_6	85.00c	20.00b	26.74c	5.15d	16.07c	17.04a	15.00e	0.197a
Ideal substrates [7]	85.00	20–30	20–30	4–10	-	-	15.00	$\leq$0.4

[1] The water content at 0 cm pressure head (saturation); [2] the air filled pores at −10 cm pressure head; [3] the amount of water released between pressure heads of −10 and −50 cm; [4] the amount of water released between pressure heads of −50 and −100 cm; [5] the amount of water released between pressure heads of −100 and −15,000 cm; [6] the amount of water held at pressure heads greater than −15,000 cm and is unavailable to plants; [7] identified by De Boodt and Verdonck [24]. [8] Columns not followed by the same letter are significant (Tukey–Kramer, at p = 0.05; n = 3).

Table 5. Measured values of water content and hydraulic conductivity at saturation (H = 0 cm) and those predicted by the Mualem–van Genuchten model at water pressure heads within the range of easily available water and water buffering capacity (H = −10, −50, −100 cm), as introduced by De Boodt and Verdonck [24], for the substrates.

H (cm)	Ps		Ps_{75}:P_{25}		Ps_{50}:P_{50}		C		C_{75}:P_{25}		C_{50}:P_{50}		Ps_{60}:P_{b30}:P_{10}		A_{70}:Ps_{24}:P_6	
	θ ($cm^3 \cdot cm^{-3}$)	K ($cm \cdot min^{-1}$)	θ ($cm^3 \cdot cm^{-3}$)	K ($cm \cdot min^{-1}$)	θ ($cm^3 \cdot cm^{-3}$)	K ($cm \cdot min^{-1}$)	θ ($cm^3 \cdot cm^{-3}$)	K ($cm \cdot min^{-1}$)	θ ($cm^3 \cdot cm^{-3}$)	K ($cm \cdot min^{-1}$)	θ ($cm^3 \cdot cm^{-3}$)	K ($cm \cdot min^{-1}$)	θ ($cm^3 \cdot cm^{-3}$)	K ($cm \cdot min^{-1}$)	θ ($cm^3 \cdot cm^{-3}$)	K ($cm \cdot min^{-1}$)
0	0.820	1.32	0.780	3.54	0.75	7.13	0.915	7.80	0.885	8.75	0.720	11.07	0.920	1.50	0.850	2.84
−10	0.748	2.8×10^{-1}	0.694	4.8×10^{-1}	0.638	5.5×10^{-1}	0.697	2.9×10^{-1}	0.650	1.6×10^{-1}	0.489	6.9×10^{-2}	0.777	8.8×10^{-2}	0.636	7.9×10^{-2}
−50	0.451	5.1×10^{-3}	0.424	8.9×10^{-3}	0.377	7.9×10^{-3}	0.381	1.5×10^{-3}	0.370	1.2×10^{-3}	0.271	7.7×10^{-4}	0.462	1.7×10^{-3}	0.383	2.4×10^{-4}
−100	0.332	4.1×10^{-4}	0.317	8.8×10^{-4}	0.286	8.0×10^{-4}	0.304	1.1×10^{-4}	0.292	1.2×10^{-4}	0.205	9.8×10^{-5}	0.340	2.1×10^{-4}	0.331	1.5×10^{-5}

3.2. Plant Growth

Plants grown in Ps_{60}:Pb_{30}:P_{10} had significantly greater both shoot dry weight and percent growth increase than the plants grown in all the other substrates, with the exception of A_{70}:Ps_{24}:P_6 in the case of percent growth increase (Table 6). Plants grown in pure coir (C) had the lowest percent growth increase. With regard to plant growth in peat-based (Ps, Ps_{50}:P_{50}, Ps_{75}:P_{25}) and coir-based (C, C_{50}:P_{50}, C_{75}:P_{25}) substrates, no significant differences were noted amongst them.

Table 6. Shoot and root dry weights at the end of the experiment and percent growth increase (%) of begonia plants throughout the duration of the experiment as affected by the substrate type.

Substrate	Shoot Dry Weight (g)	Root Dry Weight (g)	Percent Growth Increase (%)
Ps	13.01ab [1]	7.51ab	87.79ab
Ps_{75}:P_{25}	14.38ab	7.99bc	88.81bc
Ps_{50}:P_{50}	13.80ab	7.54ab	88.26abc
C	12.18a	7.08a	86.95a
C_{75}:P_{25}	12.57a	8.68cd	88.20abc
C_{50}:P_{50}	13.99ab	9.08de	89.13bc
Ps_{60}:Pb_{30}:P_{10}	20.61c	9.38e	91.64d
A_{70}:Ps_{24}:P_6	16.40b	8.77de	89.92cd

[1] Columns not followed by the same letter are significant (Tukey–Kramer, at $p = 0.05$; $n = 10$).

The analysis of both macro- and micronutrients of plant tissues are shown in Table 7. The comparison between peat and its mixtures with perlite (Ps, Ps_{50}:P_{50}, Ps_{75}:P_25) as well as coir and its mixtures with perlite (C, C_{50}:P_{50}, C_{75}:P_{25}) showed that there are no significant differences in the macro- and micronutrients measured, except in the case of K and Na for plants grown in coir-based substrates, due to the higher initial content of K and Na in coir [4]. Plants grown in Ps_{60}:Pb_{30}:P_{10} and A_{70}:Ps_{24}:P_6 had similar mineral concentrations with the abovementioned substrates for all nutrients, except for K and Mn, which were higher in plants grown in A_{70}:Ps_{24}:P_6. Note that in all treatments, the same amount of fertilizer was added to the irrigation water during the experiment, and no apparent mineral nutrient deficiency or toxicity symptoms were observed on the plants grown in all the substrates. As presented in Table 2, the two commercial prefortified substrates (Ps_{60}:Pb_{30}:P_{10} and A_{70}:Ps_{24}:P_6) had a significantly higher concentration of N, especially, than the other substrates used, giving an advantage at the early state of the cultivation. However, this was not realized at the plant tissue analysis (Table 7).

Table 7. Concentration of various macro- and micronutrients in plant tissues of *Begonia* x*elatior*, "The President", at the end of the experiment as affected by the substrate type.

Substrate	Mg	Ca	K	Na	P	N	Fe	Zn	Mn	Cu
	(%)						(μg·g^{-1})			
Ps	0.25b [1]	0.97ab	0.76a	0.28a	0.12a	1.34ab	10.02a	50.90ab	56.01a	10.60a
Ps_{75}:P_{25}	0.22ab	0.88ab	0.83a	0.28a	0.19abc	1.47ab	11.59ab	50.01ab	49.44a	10.83a
Ps_{50}:P_{50}	0.21ab	0.86a	0.77a	0.29a	0.13a	1.52ab	11.03a	49.82ab	46.95a	11.27a
C	0.17a	0.75a	1.69c	0.59b	0.19abc	0.99a	10.12a	46.21a	55.99a	10.20a
C_{75}:P_{25}	0.17a	0.68a	1.90c	0.66b	0.17ab	1.04a	9.66a	43.51a	56.44a	10.52a
C_{50}:P_{50}	0.20ab	0.80a	1.60bc	0.60b	0.20abc	1.19ab	13.79abc	46.17a	57.26a	11.06a
Ps_{60}:Pb_{30}:P_{10}	0.21ab	1.18b	1.26b	0.23a	0.26c	1.94b	20.16c	48.72ab	86.34b	12.28a
A_{70}:Ps_{24}:P_6	0.23ab	1.18b	1.87c	0.19a	0.24bc	1.86b	18.84bc	54.68b	103.2c	11.47a

[1] Columns not followed by the same letter are significant (Tukey–Kramer, at $p = 0.05$; $n = 10$).

According to Reuter and Robinson [51], the concentrations of the micronutrients Zn, Mn, and Cu are within adequate amounts. Analyses of Nelson et al. [52], which were performed on younger leaves at 5 cm width or greater size of a different *Begonia* variety to that of the current research, agree that only the Fe concentrations measured are low and the Mg concentrations are within adequate amounts for all the substrates studied. Moreover, the concentrations of N were low for all the substrates used and agree with the results given by Nelson et al. [52], obtained at the end of the cultivation.

Amongst all the substrates studied, the observed differences in nutritional status were not so significant as to solely justify the differentiation in plant growth. Additionally, although the higher values of almost all nutrient concentrations were exhibited in plants grown in the A_{70}:Ps_{24}:P_6 substrate, which was also classed as a hydraulically ideal substrate, the percent growth increase had not significantly increased in relation to Ps_{60}:Pb_{30}:P_{10} and the peat and coir mixtures. Instead, plants grown in Ps_{60}:Pb_{30}:P_{10} that had similar nutrient concentrations with plants grown in A_{70}:Ps_{24}:P_6 and was classed as hydraulically nonideal, presented significant differences in both the shoot dry weight and percent growth increase with all the other substrates studied.

Therefore, it is apparent that the physical properties of the "ideal substrates" alone (Table 4) cannot constitute the only criteria for selecting growing substrates, as there are notable substrates, such as those assessed in this paper, that did not fall within the range of the physical properties for ideal substrates. It is worth noticing that the higher plant growth was achieved in the Ps_{60}:Pb_{30}:P_{10} substrate, although it did not fall into the "ideal substrates" zone. Taking into account the hydraulic parameters of the substrates studied, the reduction of hydraulic conductivity values between two successive irrigations (at pressure heads from −10 to −50 cm) did not appear to be a limiting factor in plant growth for any substrate, "ideal" or not. In particular, K values ranged between 5.5×10^{-1} and 2.4×10^{-4} cm·min^{-1} (Table 5), or in other words, between 7920 and 3.46 mm·d^{-1}, and daily evapotranspiration values did not exceed 1.8 mm·d^{-1}, as has been determined in our previous study [14]. In any case, the knowledge of *K(H)* is essential for the substrate evaluation and proper irrigation management. So, the "nonideal" substrate Ps_{60}:Pb_{30}:P_{10} resulted in the higher plant growth because it had an adequate water flow rate (due to proper irrigation management). Additionally, Ps_{60}:Pb_{30}:P_{10} had both a growth advantage, because it was charged with a higher N concentration at the first stage of cultivation, and a high oxygen diffusion rate, as has been determined in our previous study [14].

As other researchers (e.g., [53–56]) have concluded with similar results (i.e., plants grown in substrates which did not fall in the "ideal substrates" zone showed satisfactory growth), it should be noted that these physical parameters are static and should be used only as references, because the only criterion for defining them is negative water pressure head. The important role of the dynamic hydraulic properties of the substrates such as gas diffusivity, saturated and unsaturated hydraulic conductivity, their chemical composition, and the growth particularities of different plants have not been considered.

Overall, it can be stated that because the parameters of the substrates are static, they represent steady-state conditions. However, during plant growth in pots or in the field, a dynamic state is formed that constantly changes over time and space. Therefore, the method, timing, and amount of irrigation water beyond the values of the physical properties of the "ideal substrates" (Table 2) play a significant role in defining a substrate as "ideal" or not.

4. Conclusions

The determination of physical–hydraulic properties (e.g., water retention curves, hydraulic conductivity) of the eight different substrates examined, commercial or not, used widely in floriculture, is essential to proper irrigation management. All substrates studied presented a high percentage of total porosity, available water capacity, and saturated hydraulic conductivity. The estimation of unsaturated hydraulic conductivity, K, using the Mualem–van Genuchten model showed a sharp decrease of K values in a range of water pressure heads from 0 to −50 cm. The presence of perlite in the mixes contributed to reducing the water retention ability and increasing the percentage of large pores. Knowing the particle and pore size distribution helps to create or correct the structure of substrates that are product mixtures. Also, the comparison of the substrates studied with the "ideal substrates" of De Boodt and Verdonck [24] showed that porosity alone cannot constitute a criterion for classifying substrates as "ideal" or not. Plants grown in the Ps_{60}:Pb_{30}:P_{10} substrate, classified as "nonideal", showed significantly greater growth than the plants grown in most of the other substrates studied, characterized either as "ideal" or not. The dynamic hydraulic properties of the substrates, their chemical composition, and the growth particularities of different plants should also be considered.

Author Contributions: Conceptualization, P.L.; Methodology, P.L.; Validation, P.L., A.P. and M.P.; Formal Analysis, P.L. and M.P.; Investigation, P.L.; Data Curation, P.L.; Writing-Original Draft Preparation, P.L.; Writing-Review & Editing, P.L., A.P. and M.P.; Visualization, P.L., A.P. and M.P.

Acknowledgments: We thank the KITANTZIS group of companies for the donation of the plants and substrates used in this study.

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

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