Relationship between particle size summation curves and the moisture characteristic curve for soilless substrates

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Abstract

Soilless substrates are commonly composed from multiple components with each component varying in particle density, which can affect the meaningfulness or accuracy of gravimetric particle size distribution. The objective of this study was to compare volume or weight-based methods to determine particle size distribution of single [Douglas-fir bark (DFB) only], dual (DFB plus peat or pumice), or multiple component (DFB plus peat and pumice) soilless substrates. A secondary objective was to determine if existing model of Haverkamp and Parlange can be used to predict moisture characteristic curve of single, dual or multiple component substrates with known particle size distribution. Treatment design was a 3×3 factorial with three rates each of sphagnum peat moss and pumice (0, 15, and 30% by vol) added to DFB. Particle size distribution of the nine substrates was determined using volumetric (cm^{-3}) and gravimetric methods (g). The particle size distribution of each substrate was used to determine if an existing model could be used to accurately estimate a moisture characteristic curve for each substrate. There were statistical differences in particle size distribution between volumetric and gravimetric method. This resulted in a shift in the particle size summation curve (weight or volume based), however both methods remained strongly correlated providing equivalent information. Regardless of method used for measuring particle size distribution, we were unable to develop models to predict moisture characteristic curves from particle size data.

Keywords: bark, gravimetric, peat, pumice, particle density, volumetric water content

INTRODUCTION

Soilless substrates are often manufactured from multiple components based on costs and regional availability. The individual components generally have differing physical and chemical properties, and when blended together create unique physical and chemical properties with the goal to optimize crop growth and development (Raviv and Leith, 2008; Blythe and Merhaut, 2007). Water requirements of different crops can vary significantly, and thus require additional components. Douglas-fir bark (DFB) is the primary component of soilless substrates used for containerized nursery crop production in the Pacific Northwest. Peat or pumice is often blended with DFB to achieve desired physical properties (Gabriel et al., 2009). Particle size distributions (PSD) are used as one method to describe and characterized resulting substrates (Wallach et al., 1992)

Particle size distribution curves are useful tools used when engineering soilless substrates. A PSD curve is a plot which represents the percent of the total volume of a substrate that comprises particles below a representative diameter. Soilless substrates are often composed of larger sized particles than most mineral soils, and can therefore be separated into individual particle sizes by sieving alone. This allows for fast and accurate determination of a substrate’s PSD. However, personal observations made by the authors of this paper have shown segregation of components, in part to the possible variation in particle density, within the sieve columns such as DFB: pumice substrates. The particle density of the

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organic (e.g. bark) and mineral (e.g. pumice) components used to manufacture soilless substrates can vary greatly. As a result of this, measuring PSD gravimetrically may result in incomplete measurements in substrates composed of components with different densities.

A moisture characteristic curve (MCC) is another useful tool to assess a substrate's physical properties and water holding capacity (de Boodt and Verdonck, 1972). A MCC represents the relationship of a substrate's volumetric water content to the water potential (or suction) of the substrate. A MCC, however can be time consuming to produce, with the preferred method involving the application of pressure equal to the absolute value of tension being observed, to a substrate packed in a core on a ceramic plate (Klute, 1986) or placed upon tensiometers and scale (Fields et al., 2016). Another method for developing a MCC in soilless substrates have been discussed which follow the theories first described by Buckingham (1907). In this method, a substrate is packed in a long column which is oriented vertically after saturation, allowing for drainage (Altland et al., 2010). In all of these methods, however the MCC is restricted to lower tensions, as ceramic plates, and tensiometers have finite levels of tension that can be tested, and long columns, while possible to extend as long as needed, are impractical to implement at lengths much greater than 1 m thus limiting the information gleamed from MCCs that provide information on pore size distribution and subsequent particle size.

Much research has been conducted to model particle size distribution curves in order to create MCCs in mineral soils (Arya and Paris, 1981; Haverkamp and Parlange, 1986; Smettem and Gregory, 1996; Rajkai et al., 1996; Zhuang et al., 2001). Often these models have higher accuracies with a wide range of particle sizes. This is possible because PSD can be related to the pore sizes distribution of a substrate, with larger sized particles generally contributing more macropore volume, while finer sized particles contribute more micropore volume to a substrate. The pore size can then be used to infer a MCC, as the tension at which water is held in a pore can be directly related to the diameter of that pore opening (Nimmo, 2004). Haverkamp and Parlange (1986) noted the difficulty of predicting MCC from PSD in sandy soils due to the larger particle sizes causing irregular pore sizes. The majority of components used in soilless substrates tend to be highly porous and irregular in shape. In addition, many soilless substrate components have internal porosities in which water can be absorbed. Pumice often used in the mixes with DFB has wide range of particle size, with each particle able to retain 45 to 55% water by volume internally (Boertje, 1995). Peat and bark are both able to retain up to 90 and 87% water by volume, respectively (Maher et al., 2008). As a result, it is unknown whether modeling PSD curves, similarly to work done in mineral soils, will provide accurate estimations of MCCs for soilless substrates.

The first objective of this research was to compare the PSD of soilless substrates composed of single, dual, or multiple components, measured both gravimetrically and volumetrically. This will allow for a better understanding of the accuracy of PSD curves in soilless substrates. A second objective of this research was to determine if PSD curves could be used to predict the MCC of soilless substrates using mineral soil-based methodology, in order to rapidly generate a MCC for a soilless substrate.

MATERIALS AND METHODS

General procedures

Aged Douglas-fir bark (screened to 0.9 cm) was collected from stockpiles intended for nursery container production (Marr Bros. Monmouth, OR). Pumice (<9.5 mm) (Pro-Gro, Sherwood, OR) and Canadian sphagnum peat (Sun Gro Horticulture Canada Ltd., Laval, Quebec) were used as the components to make nine substrates. The nine substrates were developed by mixing DFB with either 0, 15, or 30% of pumice or peat moss in a 3×3 factorial arrangement to generate single component (DFB only), dual component (DFB with peat or pumice), or multiple component (DFB with peat and pumice) soilless substrates. Approximately 0.11 m^3 of each substrate was prepared by mixing components with a shovel on a non-porous concrete floor. Substrates were stored individually in plastic containers in a dark, cool shed until needed for analysis.

Substrate physical properties

Douglas-fir bark samples were adjusted to 1.5 g g^{-1} mass wetness and packed in 347 cm^3 aluminum cores (7.6 cm tall by 7.6 cm i.d.) according to methods described by Fonteno and Bilderback (1993). There were three replications for each substrate. Aluminum cores were attached to North Carolina State University Porometers™ (Horticultural Substrates Laboratory, North Carolina State University, Raleigh, N.C.) for determination of D_b using oven-dried (60°C) substrate. Total porosity, container capacity, air space and D_b were reported by Zazirska et al. (2009) for all nine substrates.

Particle size

The PSD of each nine substrates based on DFB, pumice and peat was determined by drying three 1000 cm^3 oven-dried substrate (60°C) using 6.3, 4.0, 2.8, 2.0,1.4, 1.0, 0.71, 0.50, 0.35, 0.25, 0.18, and 0.11 mm soil sieves. Particles ≤0.11 mm were collected in a pan. Sieves and pan were shaken for 5 min with a RX-29/30 Ro-Tap® test sieve shaker (278 oscillations min^{-1}, 150 taps min^{-1}; W.S. Tyler, Mentor, OH). The particles from each sieve were collected to the aluminum plate on scale and expressed as a percentage of the total weight. To determine the volume of the particles, materials was packed into graduated cylinders (250 or 500 mL) and tapped three times on the table surface, after which actual volume was recorded and expressed as a percentage of a total volume. Weight of substrate from graduated cylinder was recorded and used to calculate the D_b of each particle size for each of the nine substrates.

Statistics

Particle summation curves and MCC were fit using a four-parameter log-logistic model [$y=a+(c/(1+(x/x_0)^b))$] where a=the minima plateau, $a + c$=the maxima plateau, x=the independent variable, x_0=the inflection point where the sigmoid curve transitions from convex to concave, and b=the air entry value. Moisture characteristic curves were determined by solving for a, c, x_0, and b, and are reported by Gabriel et al. (2009) for all nine substrates. Models were fit using Proc NLIN in SAS (SAS Institute, Cary, N.C.). Models for particle summation curves were fit by setting a=0 and $(a + c)$=100 and solving for b and x_0. Particle size density was subject to multivariate analysis of variance and comparison the gravimetric versus volumetric method each of the nine substrates within a particle size fraction (sieve) using an F-test.

RESULTS AND DISCUSSION

Volumetric and gravimetric means to determine particle size distribution differ with soilless substrates containing single (bark only), dual (bark with peat or pumice), or multiple components (bark with peat and pumice). The single component system containing bark only had differences in measured particle size < 1 mm when using a volumetric versus gravimetric method (Table 1). The weight-based method increased the number of particles occurring below 0.71 mm (p-value=0.02, F-value=14.61), whereas the volumetric method resulted in a combined decrease of 1.14% for particles occurring between<0.71 mm (Table 2). This increase results in a shift of the particle size summation curve to the right (Figure 1) changing the interpretation of the bark texture and subsequent decreased relative porosity. The shift or increased number of particles less than 0.35 mm observed using gravimetric analysis also occurred when adding peat or pumice to make a dual component substrate.

Bark substrates with peat additions (15 or 30% by vol.), the number of fine particles (<0.10 to 0.34 mm) was greater using the gravimetric method versus volumetric (p-value=0.0068, F-value=26.40). In addition, significant differences in the two methods occurred with larger particle sizes; <2mm (p-value=0.0114, F-value=19.63) and <2.8 (p-value=0.0192, F-value=14.39) for substrates containing 15 and 30% (by vol) peat, respectively (Table 1). Increasing addition of peat measured gravimetrically did not show noticeable shifts in the particle size summation curve (Figure 2B); however, the shift is more gradual and discernable when employing the volumetric method (Figure 2A).

Table 1. Particle size distribution by weight (g) and by volume (cm-3) of nine soilless substrates with varying ratios of Douglas-fir bark (DFB), pumice, and peat.

Component	Rate	Analysis	Particle size (mm)												
			<0.10	**0.11-0.17**	**0.18-0.24**	**0.25-0.34**	**0.35-0.49**	**0.50-0.70**	**0.71- 0.99**	**1.00-1.39**	**1.40-1.99**	**2.00-2.79**	**2.80-3.99**	**4.00-6.29**	**>6.30**
									Single component						
DFB		Weight	2.19	3.73	5.16	7.21	8.53	9.39	8.47	9.55	11.78	12.74	12.60	8.34	0.32
		Volume	1.37	2.94	4.31	6.49	9.08	10.48	8.87	10.36	12.54	13.06	12.41	7.58	0.51
									Dual component						
DFB plus pumice	15	Weight	3.47	2.89	3.52	5.16	6.85	8.80	8.53	9.93	11.87	12.67	13.29	10.66	2.37
		Volume	2.04	2.24	2.88	5.23	8.08	9.90	9.48	10.71	13.06	12.57	12.88	9.27	1.65
	30	Weight	5.34	2.84	3.00	4.41	5.85	7.63	7.73	9.59	11.96	12.96	13.62	11.30	3.76
		Volume	3.03	2.23	2.63	4.39	5.87	8.29	8.65	10.29	13.07	13.48	13.57	11.33	3.15
DFB plus peat	15	Weight	1.84	3.40	4.66	6.63	8.30	9.98	9.35	10.00	11.73	12.74	12.20	8.34	0.82
		Volume	1.00	2.19	3.69	5.86	8.65	11.36	10.92	10.61	12.76	12.73	11.60	7.62	1.03
	30	Weight	2.11	3.11	4.59	6.83	8.46	10.19	9.37	9.86	11.16	12.03	11.94	8.34	1.99
		Volume	0.98	2.08	3.65	6.24	8.52	11.50	10.86	10.90	11.64	11.25	11.12	7.81	3.45
									Multiple component						
DFB plus peat:pumice	15:15	Weight	2.69	2.88	3.41	5.73	7.03	9.15	9.06	10.41	12.27	9.67	13.42	11.36	2.92
		Volume	1.33	2.03	2.78	4.89	7.09	10.29	10.09	11.21	12.74	12.62	12.54	9.59	2.80
	15:30	Weight	3.36	2.00	2.17	3.25	5.20	8.26	8.72	9.96	12.44	13.97	14.22	12.35	4.11
		Volume	1.90	1.58	1.95	3.18	4.79	7.86	8.82	10.63	13.37	14.42	13.71	12.50	5.30
	30:15	Weight	2.45	2.00	2.23	3.20	4.68	7.36	8.59	10.64	12.88	13.84	14.20	13.07	4.86
		Volume	1.10	1.40	1.82	2.96	4.31	7.66	9.82	12.02	14.09	14.13	13.65	11.86	5.18
	30:30	Weight	3.77	2.17	2.37	3.76	6.05	7.64	7.90	9.64	11.70	12.54	13.16	13.68	5.62
		Volume	1.77	1.58	2.00	3.51	8.86	8.59	8.83	10.14	12.10	12.10	12.05	12.11	6.37
p-value			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.07	0.03	0.35	0.001	<0.0001	<0.0001
p-value			<0.0001	<0.0001	<0.0001	<0.0001	0.05	<0.0001	<0.0001	0.01	0.01	<0.0001	<0.0001	<0.0001	<0.0001
Multivariate main effects									Pr > F						
Treatment									<0.0001						
Method									<0.0001						
Interaction									<0.0001						

Table 2. Particle size distribution on a volumetric or gravimetric basis of Douglas fir bark, peat, and pumice expressed as a percentage of the whole.

Component	**Particle size (mm)**												
	<0.10	**0.11-0.17**	**0.18-0.24**	**0.25-0.34**	**0.35-0.49**	**0.50-0.70**	**0.71-0.99**	**1.00-1.39**	**1.40-1.99**	**2.00-2.79**	**2.80-3.99**	**4.00-6.29**	**>6.30**
	Volumetric analysis (cm^{-3})												
Bark	1.37	2.94	4.31	6.49	9.08	10.48	8.87	10.36	12.54	13.06	12.41	7.58	0.51
Peat	5.30	0.54	0.23	0.25	0.35	0.54	0.72	1.30	3.37	10.41	18.35	36.21	22.44
Pumice	1.33	3.90	5.24	8.20	10.58	11.74	10.59	6.56	6.25	5.75	7.91	10.86	11.09
	Gravimetric analysis (g)												
Bark	2.19	3.73	5.16	7.21	8.53	9.39	8.47	9.55	11.78	12.74	12.60	8.34	0.32
Peat	8.59	0.84	0.40	0.45	0.74	1.22	1.30	1.65	3.64	10.65	18.00	31.71	20.82
Pumice	3.68	7.99	6.23	8.80	9.98	11.20	7.87	5.62	5.27	5.47	6.79	10.70	10.39

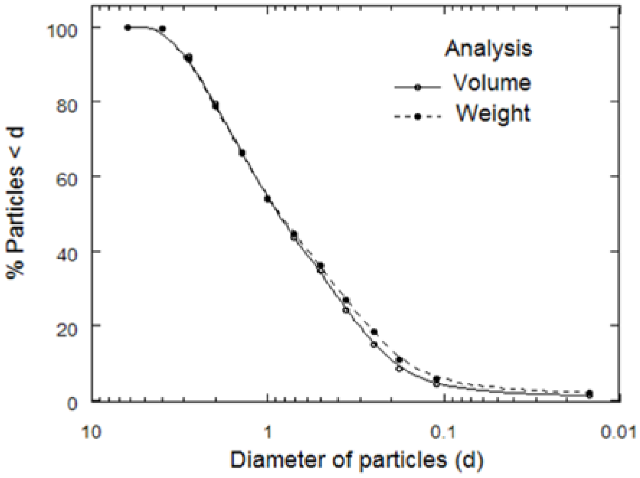

Figure 1. Particle size summation curve for a single component soilless substrate (DFB only) determined using volumetric and gravimetric method.

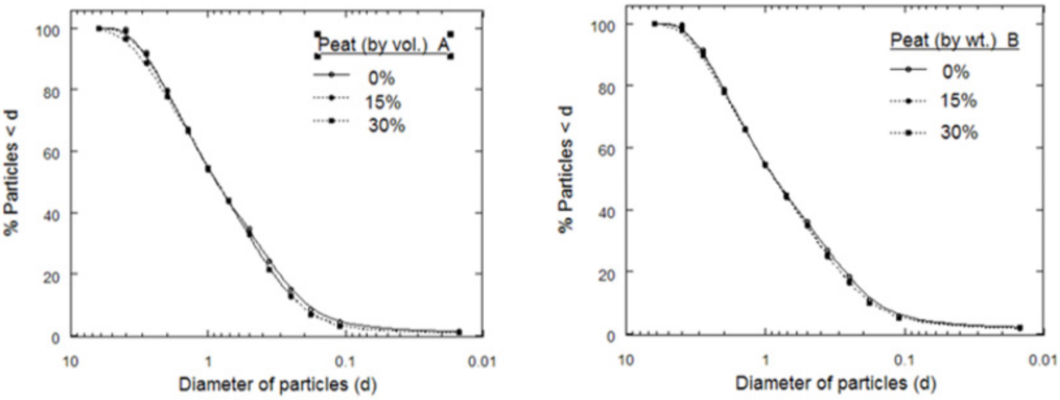

Figure 2. Particle size summation curve for a dual component soilless substrate (DFB and 15% and 30% peat) determined using volumetric (A) and gravimetric (B) method.

With 15 or 30% (by vol.) addition of pumice to DFB, both ends of the particle size spectrum differed when measured using the gravimetric or volumetric method (Table 1). This resulted in the particle size distribution curve being shifted to the left with increasing additions of pumice indicating a coarser texture substrate. The volumetric method (Figure 3A) showed a more gradual shift in the particle summation curve relative to the addition of pumice, whereas the gravimetric method (Figure 3B) illustrated one large shift with either an addition of 15 or 30% (by vol) pumice.

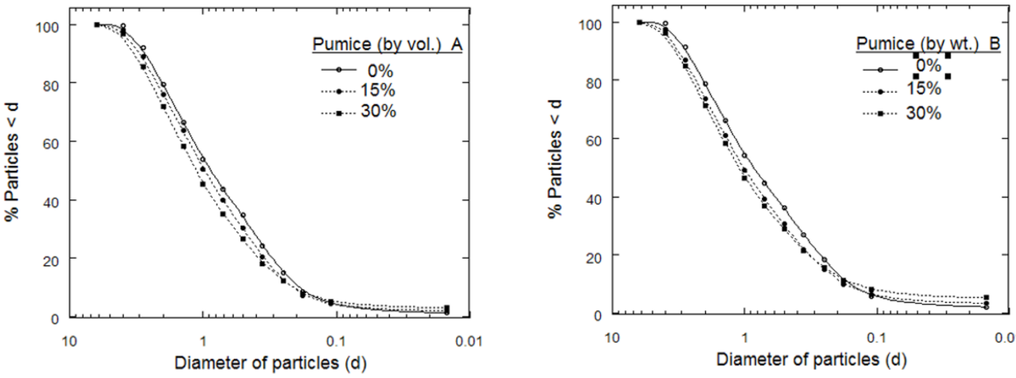

Figure 3. Particle size summation curve for a dual component soilless substrate (DFB and pumice) determined using volumetric (A) and gravimetric (B) method.

In multi-component substrates containing 15:15%, 15:30%, 30:15% and 30:30% (by vol) additions of peat and pumice to DFB resulted in the amount of measured particles for a given fraction to differ if the volumetric or gravimetric method was used; however, neither peat nor pumice seemed to have greater influence on the results. Volumetric versus gravimetric based measures of particle size, with increasing pumice, showed more significant difference when peat increased from 15 to 30% (by vol.; Table 1). The volumetric and gravimetric method to measure particles size were similar when peat was varied within a DFB substrate amended with 15 or 30% (by vol.) pumice. Increasing either peat or pumice from 0 to 30% (by vol.) in the presence of a constant addition of either other component resulted in the summation curve shifting to the left indicating a more coarse substrate. This shift was much more discernable for increasing peat when pumice was present at the highest rate (30% by vol.). All shifts in summation curve were more notable if the volumetric method was employed. The gravimetric method resulted in particle summation curves shifting to the right compared to those measured volumetrically. The particle size distributions remain strongly related regardless of the variation occurring between the gravimetric and volumetric methods. When looking across substrates (single, dual, and multi-component), both x_0 and b were strongly correlated with R^2=0.94 and R^2=0.80, respectively (data not presented).

Regardless on variation of particle density between components; the gravimetric method curves were more similar to volumetric measurements. Nevertheless, the volumetric method appears to create more discernable, informative summation curves; however, this method may have an inherent error because D_b is variable across particle size ranges and nesting of particles effecting total substrate volume. The overall trend was that D_b decreased with increasing particle size (data not presented). Overall D_b of these three components were not uniform, with peat (D_b=0.07 g cm^{-3}), DFB (D_b=0.16 g cm^{-3}), pumice (D_b=0.41 g cm^{-3}).

An attempt was made to predict MCC from either volumetric or gravimetric particle summation curves using a modified Haverkamp and Parlange method. Because a and (a + c) are set to 0 and 100, respectively, for particle summation curves, only x_0 and b need to be predicted to complete the sigmoid model. Correlations between x_0 of particle summation curves (volumetric or gravimetric) and MCC were poor. There was similarly poor correlation among the analytical methods for b (Figure 4). Therefore, we were unable to predict a MCC from particle summation curves in the nine substrates evaluated herein. Similar modeling between particle summation curves and MCC in mineral soils used samples ranging from gravels to clays, which vary widely in physical and hydraulic properties.

Soilless substrates evaluated herein do not have adequate variation in particle size distribution or matric potential at a given volumetric water content to reveal the relationship between the two analytical methods. However, differences can be measured with particle summation curves and MCC of the nine substrates evaluated in this paper that represent the range of substrates used in nursery production. Substrate with greater variation of these parameters may have an increased chance of predictability.

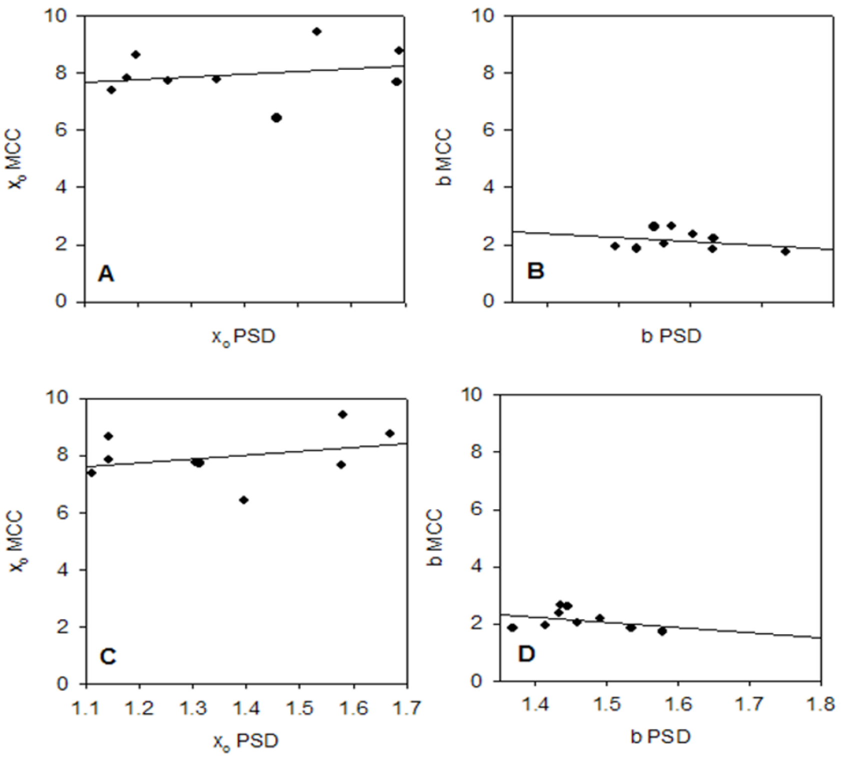

Figure 4. Correlation between x_0 (A, C) and b (B, D) for moisture characteristic curve and particle size summation curve of nine soilless substrates (DFB plus peat and/or pumice) determined using volumetric (A, B) and gravimetric (C, D) method. A. $y=0.914x+6.682$, $R^2=0.0495$; B, $y=-1.3324x +4.2557$, $R^2=0.0751$; C, $y=1.4093x+6.0367$, $R^2=0.1153$; D, $y=-1.8459x+4.8355$, $R^2=0.1168$.

CONCLUSIONS

Either a volumetric or gravimetric method of measuring particle size distribution is informative. The volumetric method creates more discernable shift in the summation curve when amended with components that dramatically alter physical properties such as air space; however, both methods are inherently flawed. The gravimetric method cannot be easily corrected for the large variation in particle density of components used in soilless substrates. Bulk density varied across particles size when using the volumetric method, overestimating distribution of large pores that will be filled with small particles. Neither method created particle summation curves that were similar to the moisture characteristic curve generated for the like substrate, making it impossible to predict the hydrology of the substrate. In addition, this approach was unable to take into account the physical properties and hydrology of the actual component particles which also effect matric potential. More basic research is needed with single component system to understand the relationship of particle size distribution to pore distribution in soilless substrate systems.

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