HortScience 57(6):715–725. 2022. https://doi.org/10.21273/HORTSCI16583-22

A Review and Analysis of Horticultural Substrate Characterization by Sieve Analysis

Paul C. Bartley III, William C. Fonteno, and Brian E. Jackson
Department of Horticultural Sciences, North Carolina State University, Raleigh, NC 27695

Additional index words. coconut coir, particle size analysis, particle size distribution, peat, perlite, pine bark, screen

Abstract. **The physical, hydrological, and physico-chemical properties of horticultural substrates are influenced by particle shape and size. Sieve analysis has been the predominate method used to characterize the particle size distribution of horticultural substrates. However, the literature shows a diversity of techniques and procedures. The effects of agitation time and sample size on particle size distributions of soilless substrates were evaluated for several measures of sieve analysis, including sieve rate (a calculation of the percentage of material passed for each unit time of agitation), distribution median, SD, mass relative span, skewness, and kurtosis. To obtain the standard sieve rate (0.1%/min), pine bark, peat, perlite, and coir required agitation times of 4 minutes and 47 seconds, 7 minutes and 18 seconds, 10 minutes, and 11 minutes, respectively. However, there was concern that unwanted particle breakdown may occur during the particle size analysis of some materials. Therefore, a sieve rate (0.15%/min) for more friable materials was also determined. As a result, the endpoint of sieving was reached sooner for pine bark, peat, perlite, and coir, at 3 minutes and 10 seconds, 4 minutes and 42 seconds, 5 minutes and 14 seconds, and 6 minutes and 24 seconds, respectively. Increasing agitation time resulted in decreased distribution median, SD, and skewness for all materials. Sample sizes half and twice the volume of the recommended initial volume sieved did not change particle size distributions. For more precise characterization of particle size distributions when characterizing substrate components, agitation times and sample sizes should be specified for each material or collectively for all materials to ensure consistency and allow comparisons between results.**

The effects of particle size on the properties of aggregate materials have been a focal point for a diversity of research fields, from pharmaceutical drugs to biofuels (Bitra et al., 2009; Brittain, 2002; Fernlund, 2005). Horticultural substrates are routinely classified as aggregate materials by particle size (Handreck, 1983). The physical properties of substrates (i.e., bulk density and porosity) are, mostly, consequences of the particle size distribution (PSD) of a material or blend of materials (Anicua-Sanchez et al., 2008; Bunt, 1983; Pokorny and Henny, 1984). Additionally, differences in the hydrological properties of substrates (i.e., water holding capacity and hydraulic conductivity) are mostly defined by the different pore characteristics imparted by particle size and particle arrangement (Bunt, 1983; Gabriel et al., 2009; Jones and Or, 1998; Pokorny and Henny, 1984). Particle size analysis (PSA) is used as a metric to indicate differences between materials or as predictive models to derive physical properties (Pokorny, 1993).

Sieve analysis is one of the most basic tests for fractioning particle sizes of aggregate materials and is the predominate method for PSA of horticultural substrates (Allen, 1997; Handreck, 1983). A sieve consists of a wire mesh screen that is fixed to the base of an open cylindrical container. Screens comprise woven wires containing openings (apertures) with a fixed sized. The act of sieving involves agitating a sample within a sieve. The resulting agitation allows particles with dimensions smaller than the apertures to pass through the screen. Sieves can be stacked one on top of another, in decreasing aperture sizes, to create what is called a "nest" of sieves (Fig. 1). The process of passing a material through decreasing aperture sizes allows the sample to be fractioned by aperture size. The fraction of the initial sample retained in each sieve is collected by brushing or tapping; then, it is weighed. Data may be more easily recorded by weighing the sieve before and after a sample is run. To accurately characterize a material, replications of the sample are required. Typically, PSA data are expressed as the mean of the mass collected for each sieve size or as the mean fraction of the initial material's mass and deviation of the mean.

Because of its simplicity, sieve analysis remains the most popular method of determining PSD; however, reproducibility and misapplication issues have limited how effective these results have been (Allen, 1997; Carpenter and Deitz, 1950; Syvitski, 1991). However, the accuracy and reproducibility of sieve analysis can be improved if standardized sieving procedures are considered (Allen, 1997; Gee and Or, 2002). Currently, sieving standards have been implemented for horticultural substrates through the European Standards (EN), but not through a U.S. standards system, such as the American Society for Testing and Materials (ASTM) Standards (European Standards, 2007). This lack of standardization has resulted in many different approaches to PSA from a diverse group of horticultural substrate researchers.

A review of 20 domestic and international studies that assessed the physical properties of horticultural soilless substrate materials revealed a diversity of techniques and procedures used to conduct sieve analyses. For a particle size analysis to be reproducible, it would be beneficial to know the material, method of agitation, agitation time, sieve sizes, and sample size (mass or volume). The variability of PSA procedures from these 20 publications is provided in Table 1. The sample size ranged from 100 to 150 g if reported by weight and from 100 to 500 cm^3 if reported by volume. The agitation times used to conduct PSA ranged from 1 to 20 min. Of the 20 publications reviewed, only three publications by differing authors implemented the same procedures for sieve analysis (Bilderback, 1985; Drzal et al., 1999; Jackson et al., 2010; Richard, 2006). In several publications, criteria beneficial to the reproducibility of the work were omitted (Bachman and Metzger, 2007; Dumroese et al., 2011; Richards et al., 1986). Because of the lack of consistency in sieving protocols, empirical data are difficult to compare between studies.

Many publications and current standards that discuss sieving protocols, such as ASTM D6913 (2009), describe the procedures for obtaining PSD (gradation) using sieve analyses for soils and "other objects." However, horticultural substrates vary greatly in size and shape compared with soil; therefore, they may necessitate additional work to create a standard of their own. Although EN 15428 (2007) was developed specifically for obtaining the PSD of organic materials, the methods practiced in Europe differ from those preferred in the United States (discussed in more detail later). Although the work required to develop a U.S. or international standard in its entirety is beyond the scope of this work, at the very least, a review of the potential sources of error should be conducted to increase reproducibly and consistency for future projects involving the PSA of horticultural substrates. The errors in sieve analysis originate from three primary sources: 1) the sieves, 2) the method of shaking, and 3) the sample.

Received for publication 4 Mar. 2022. Accepted for publication 5 Apr. 2022.
Published online 20 May 2022.
Current address for P.C.B.: Assistant Professor, Department of Horticulture, Auburn University, Auburn, AL 36849
B.E.J. is the corresponding author. E-mail: brian_jackson@ncsu.edu.

Fig. 1. A nest of sieves (brass) and pan (steel) agitated by a Tyler Ro-Tap machine.

The sieves. Sieves are one of the only tools available that can sort an aggregate material solely based on particle size and independent of a material's density, surface texture, or chemistry (Allen, 1997). The ideal sieve contains apertures that are perfectly square or round and are of a given size (Allen, 1997; Brittain, 2002). To obtain an adequate profile of particle distributions, aperture sizes were initially set on a progression of the square root of two (≈1.414) based on 75 μm (Allen, 1997). Using the square root of two progression, the aperture area of a sieve is twice that of the next finer sieve. Many modern screen aperture standards are based on the fourth root of two (≈1.189) progression to allow for closer sizing between adjacent sieves (Allen, 1997; ASTM, 2001; Brittain, 2002; EN, 2007). The U.S. Standard Sieve Series is based on an opening of 1 μm and is further described in ASTM E11 (2001). The EN comply with the standards implemented by the International Standards Organization (ISO) (EN, 2007). The ISO recognizes four sieve series, R 20/3, R 10, R 40/3, and R 20. The R 20/3 series is based on the original square root of two progression, whereas the R 40/3 series is based on the modern fourth root of two progression (ISO, 1990). Hence, the U.S. Standard Sieve Series and the R 40/3 sieve series are identical and could be used interchangeably (Brittain, 2002).

Because particles are sorted by the apertures of screens, any deviation or variance in the apertures may result in error. Woven wires produce three-dimensional apertures with considerable tolerances to allow for the relative to the size of the aperture (Allen, 1997; ASTM, 2001; ISO, 2016). As the aperture size decreases, relative tolerance increases, which may result in several apertures of similar sizes on multiple sieves. For example, the ASTM permits a median ranging from 70 to 80 μm with no more than 5% of the apertures in the range of 91 to 103 μm for a 75-μm sieve (ASTM, 2001). Based on this example, a particle with a limiting dimension (second smallest cross-sectional dimension) of 100 μm could be captured in a 75-μm, 90-μm, or 106-μm sieve. Although sieve sizes ranging from 75 to 105 μm are rarely used in the PSA of horticultural substrates, studies have used sieves with equal or smaller aperture sizes (Fain et al., 2008; Jackson et al., 2010). Because of tolerance ranges, the same material analyzed by two different sets of sieves may show differences in its PSD (Allen, 1997; Syvitski, 1991).

Analytical variance between sieve sets could also be attributed to damaged screens. Damage to screens (as seen in Fig. 2A) may result in deviations of aperture sizes beyond the tolerated range and may reduce the precision of the sieve to separate particles appropriately. Screen damage can also manifest itself as dimpled or raised imperfections, resulting in improper particulate distribution across the screen (as seen in Fig. 2C). Particles will inadvertently congregate to depressions in the screen, reducing the area of open space encountered by the sample and introducing an error called the "blinding effect" (Carpenter and Deitz, 1950; Shergold, 1946). The blinding effect occurs when the sample load on a screen is such that all openings become plugged or blocked, preventing smaller particles from passing appropriately (Allen, 1997; Shergold, 1946). Because a particle's probability of passage is relative to its encounter with an open space, any depletion of open space on the screen's surface caused by trapped particles or damaged screens would result in errors during the analysis (Fig. 2B).

To reduce errors attributed to sieves, a methodical examination of potential sieve sizes before application is required. A well-lit background can be used to detect any screen defects such as creases, projections, and entrapped particles. These obvious defects can be detectable to the untrained eye; however, more detailed defects, such as aperture tolerance, may be detectable only by a skilled observer. A complete inspection procedure can be found in the annex of ASTM E11 (2001).

The method of shaking. The method of shaking or agitation of a given sample can be either shaking by hand or shaking using a mechanical instrument. Because of the nature of standardizing protocols, any agitation instrument must be able to reproduce the result of manual agitation. Mechanical instruments can agitate material by means of vibration or a combination of gyratory and jolting movement. The former method, vibration, is the agitation means used in accordance with EN Standards. The latter is generally preferred for horticultural research in the United States (Altland and Krause, 2012; Drzal et al., 1999; Pokorny and Henny, 1984). The gyratory and jolting (tapping) movement may be preferred over other methods because it reduces aperture blockage and increases reproducibility (Allen, 1997). Because of differences between agitation techniques, the

Table 1. Variability in sieve analysis procedures implemented to characterize horticultural substrates.

Publication	Material	Agitation method[z]	Agitation time	Sieve sizes (yes/no)[y]	Sample size
Abad et al. (2005)	Coir	Vibration	10 min	Yes	200 cm[x]
Altland and Krause (2012)	Pine bark/wood	Ro-Tap	3 min	Yes	100 cm[x]
Bachman and Metzger (2007)	Compost	N/A[3]	N/A	Yes	100 g
Bilderback (1985)+[w]	Bark	Ro-Tap	5 min	Yes	100 g
Buamscha et al. (2007)	Douglas fir bark	Ro-Tap	5 min	Yes	N/A
Bunt (1983)	Peat	N/A	N/A	Yes	N/A
Caron et al. (2005)	Peat, pine bark, sand	Hand	1 min	Yes	500 cm[x]
Drzal et al. (1999)+	Blended materials	Ro-Tap	5 min	Yes	100 g
Dumroese et al. (2011)	Peat, biochar	N/A	N/A	Yes	N/A
Fain et al. (2008)	Pine bark/wood	Ro-Tap	3 min	Yes	100 g
Jackson et al. (2008)	Pine bark/wood	Ro-Tap	10 min	Yes	150 g
Nemati et al. (2009)	Peat	Vibration	6 min	Yes	250 cm[x]
Nemati et al. (2015)	Biochar	Vibration	2 min	Yes	250 cm[x]
Noguera et al. (2003)	Coir	Vibration	N/A	Yes	N/A
Northup (2013)	Biochar	N/A	N/A	Yes	N/A
Owen et al. (2007)	Pine bark, clay	Ro-Tap	5 min	Yes	500 cm[x]
Pokorny and Henny (1984)	Pine bark, sand	Ro-Tap	20 min	Yes	250 cm[x]
Richard (2006)+	Pine bark	Ro-Tap	5 min	Yes	100 g
Richards et al. (1986)	Pine bark, sand, coal	Mechanical	N/A	Yes	N/A
Sambo et al. (2008)	Peat, rice hulls	N/A	2 min	Yes	100 g

[z]Agitation method is listed as reported in each publication.
[y]"Yes" and "No" indicate whether sieves sizes were reported in each publication.
[x]Not reported in the publication.
[w]The "+" signifies the same procedure was implemented.

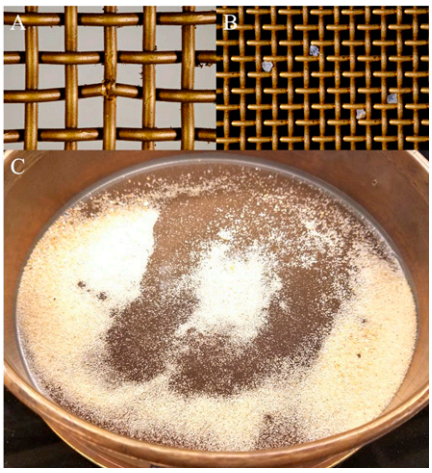

Fig. 2. Variability in aperture size and obstructions within apertures may result in errors when using sieve for particle size analysis. (**A**) Damaged woven wire screens can decrease or increase aperture sizes beyond that of the tolerated deviation allowed by American Society for Testing and Materials (ASTM) Standards. (**B**) Entrapped particles will diminish the percentage of open apertures. (**C**) Raised areas or depression on a sieve screen will result in poor sample distribution (photo credit: David Suchoff).

method used and duration of agitation should always be reported. The duration of agitation is important because the probability of a particle passing within a given time is dependent on the particle size, shape, and orientation relative to the sieve aperture (Day, 1965). Particle passage with regard to agitation time determines the "sieve rate" of a material, which is also referred to as the "convergence rate" (Carpenter and Deitz, 1950).

The sieve rate is a calculation of the percentage of material passed for each unit of time at a given sieve size. The sieve rate of a material has been described to consist of two regions, the initial region and the "near-mesh particle size" region (Allen, 1997). Initially, the rate of change by time will decrease sharply as particles with dimensions much smaller than the screen's aperture size readily pass. As time increases, the sieve rate decreases as particles with near-mesh size dimensions must find the proper orientation in which to pass. The end goal of sieving would be attained when all sieve rates are zero (i.e., no more material passed through any sieves). However, it would be unlikely for complete sorting of a material to occur. There will always be a chance that the ideal particle may find one aperture large enough to pass in the one orientation that may allow it (Allen, 1997).

For sieve analysis to be reproducible the sieve rate must be low enough so that 1 min too long or too short would not affect the results significantly (Carpenter and Deitz, 1950; ISO, 1988). ASTM suggests the "standard shaking period" should be between 10 and 20 min for soils and include a simplistic procedure to determine the sieve rate (ASTM, 2009). The sieve rate for soils is determined by first agitating a sample for 10 min for a single sieve-set. Beginning with the largest sieve in the set, fix a lid above and a pan below the sieve and shake by hand for 1 min. If the ratio of the material's mass in the pan to the material retained in each sieve changes by less than 0.5%, then the analysis is deemed complete. If the ratio is greater than 0.5%, then the shaking period must be increased and checked incrementally until the criterion is met. The EN standard suggests agitating a sample for 7 min with the use of a vibration table for soil improvers (compost) and growing media (EN, 2007). Using this method, the sieve rate is not determined by time, but instead by three amplitude settings (range, 0.5–1.5 mm) that best sorted the material.

The sample. As exhibited by the initial and near-mesh size regions of sieve rates, the probability of a particle passing through a screen within a given time is dependent on the particle's shape and size. Therefore, the physical characteristics of a sample are pivotal with regard to its sievability and interpretation of PSA (Allen, 1997). Sample characteristics that affect PSA can be attributed to the material or individual particles of the material. For example, a high moisture content in a sample may cause particles to clump and to be sorted improperly. Therefore, a moisture content of less than 15% is recommended for soils and organic materials (ASTM, 2001; EN, 2007). Clumping of particles can also be observed if the sample contains a portion of fibrous particles that cling to one another during agitation (Fig. 3). Other characteristics that may affect PSA include sample size, particle shape, and particle size.

The blinding effect on screens, previously discussed as influenced by screen damage, is primarily influenced by excessive sample sizes. Prohibitive sample loads on a given sieve reduce the probability of a particle's passage so that compensation cannot be provided by any extended amount of agitation time (Shergold, 1946). The load on a given sieve is considered ideal at a depth of one or two particles (Allen, 1997; Carpenter and Deitz, 1950; Shergold, 1946). Carpenter and Deitz (1950) recommended a load of material no more than six particles deep in each sieve to reduce the blinding effect. Shergold (1946) observed that blinding increased in smaller aperture sizes, insinuating that a sample's particle size should dictate the sample size. European standards for growing media also suggest that the sample size should be selected based on particle size (EN, 2007). If less than 50% of the sample passes an 8-mm screen, then the sample size should be 375 mL for a 200-mm (8-inch) sieve. If more than 50% passes, then the sample size should be

Fig. 3. Fibrous particles, like this *Juniperus virginiana* bark, commonly aggregate on a screen when agitated by a Ro-Tap machine. This does not allow the material to be properly sorted for accurate particle size analysis.

Table 2. Guide to the quantity of material that the International Standards Organizations (ISO) recommends for test sieving on a 200-mm-diameter round sieve.[z]

	Bulk volume of material[y]			Bulk volume of material	
Aperture size (mm)	Volume of charge	Volume of residue[x]	Aperture size (μm)	Volume of charge	Volume of residue
22.4	1600	800	710	120	60
16.0	1000	500	500	100	50
11.2	800	400	355	80	40
8.0	500	250	250	70	35
5.6	400	200	180	60	30
4.0	350	175	125	50	25
2.8	240	120	90	42	21
2.0	200	100	63	35	17
1.4	160	80	45	30	15
1.0	140	70	32	26	13

[z]Table data replicated from ISO 2591 (1988).

[y]Masses of materials can be determined by multiplying the values specified in columns 2 and 3 and columns 5 and 6 by the apparent bulk density (in grams per cubic centimeter) of the material to be sieved.

[x]Maximum volume of material permitted on the sieve after sieving has been completed.

125 mL for the same sized sieve. According to ISO 2591 (1988), the quantity of material to be placed on a sieve depends on the aperture size, bulk density of the material, area of the sieve, and proportion of oversized material. Volumetric guidelines for the initial sample size (charge) and maximum volume of residue are provided for each sieve size (ISO, 1988) (Table 2). Although the amount of sample to be used may be subjective to the material and its sievability, subjection to consistent guidelines for sample size selection may result in increased consistency and reproducibility (Allen, 1997; ISO, 1988).

Sieves allow the passage of a particle by the second smallest dimension or the intermediate dimension. This dimension is generally referred to as the particle's width when it is at a steady state (most stable position). From this point forward, a particle's intermediate dimension will be referred to as the particle's

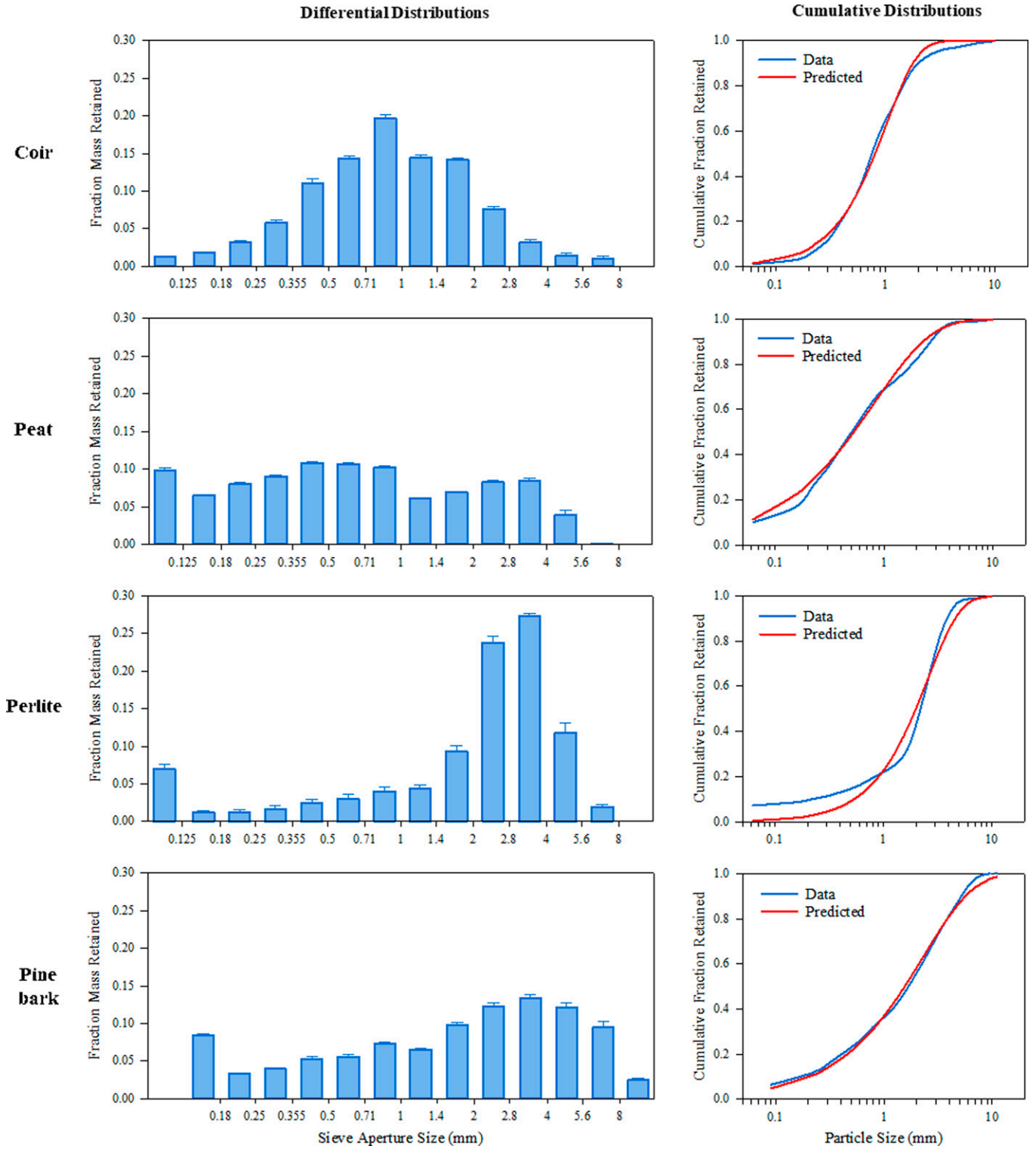

Fig. 4. Log-normal differential and cumulative distributions of coir, peat, perlite, and pine bark following an agitation period of 5 min. Cumulative retained mass fraction data were regressed using the Rosin-Rammler distribution function, a Weibull cumulative distribution function used to model predicted distributions (Rosin and Rammler, 1933).

"true sieve size" because it is impossible for the particle to pass through an aperture of smaller dimensions. The probability of a particle being fractioned to its true sieve size is theoretically dependent on the particle form and length (the largest of three dimensions) (Allen, 1997; Fernlund, 1998; Syvitski, 1991). Therefore, the probability of a particle being captured on a sieve larger than its true sieve size is dependent on its shape, size, and likeliness (or unlikeliness) to obtain the proper orientation for passage. The proper orientation for passage is relative to the particle length (Bartley et al., 2019; Gee and Or, 2002; Syvitski, 1991). This is supported by Bartley et al. (2019), who found that the higher the aspect ratio (ratio of length to width) of the particle, the lower the precision of sieve analysis, especially for a particle with an aspect ratio of 3:1 or more. As particle length increases, the angle of the largest dimension with regard to the plane of the screen must also increase to allow passage. Shapes and sizes that do not obtain the proper orientation result in an apparent coarsening of the material in the analysis (Bartley et al., 2019; Syvitski, 1991).

The significance of these conclusions has implications for sieving horticultural substrates. Perlite's spherical shape would allow it to be quickly and accurately sorted as long as other potential sources of error (i.e., damaged screens and sample size) are considered. Complex shapes and heterogeneous materials, such as sphagnum peat, wood fiber, and pine bark, may be difficult to accurately sort and characterize using sieve analysis. Considering the diversity of horticultural substrates, it may be beneficial if the protocols for sieve analysis reflect a material's inherent sievability.

Considering the variety of published sieving procedures, potential sources of error, and inherent sievability of materials, it was hypothesized that a sieve rate analysis of common substrate components could elucidate the effects of agitation time and sample size on PSA. Sieve rates have not been reported, even generically, for many horticultural substrate components and could be examined for sieving optimization and reproducibility. For many fragile organic and inorganic materials like peat, pine bark, or perlite, the rate of sieving may continue to change significantly with time. In this case, it may be better to choose a shorter time interval. Because agitation time increases, changes in particle distribution could be indicative of the sorting of near-mesh size particles and particle attrition caused by the machine's energetics (Carpenter and Deitz, 1950). Although sieve rates may be specific to the material and sieve set, a general understanding of a substrate component's sieve rates could lead to better optimization and higher reproducibility. Therefore, the objective of this research was to investigate the effects of agitation time and samples size on substrate PSA by evaluating the substrate sieve rate.

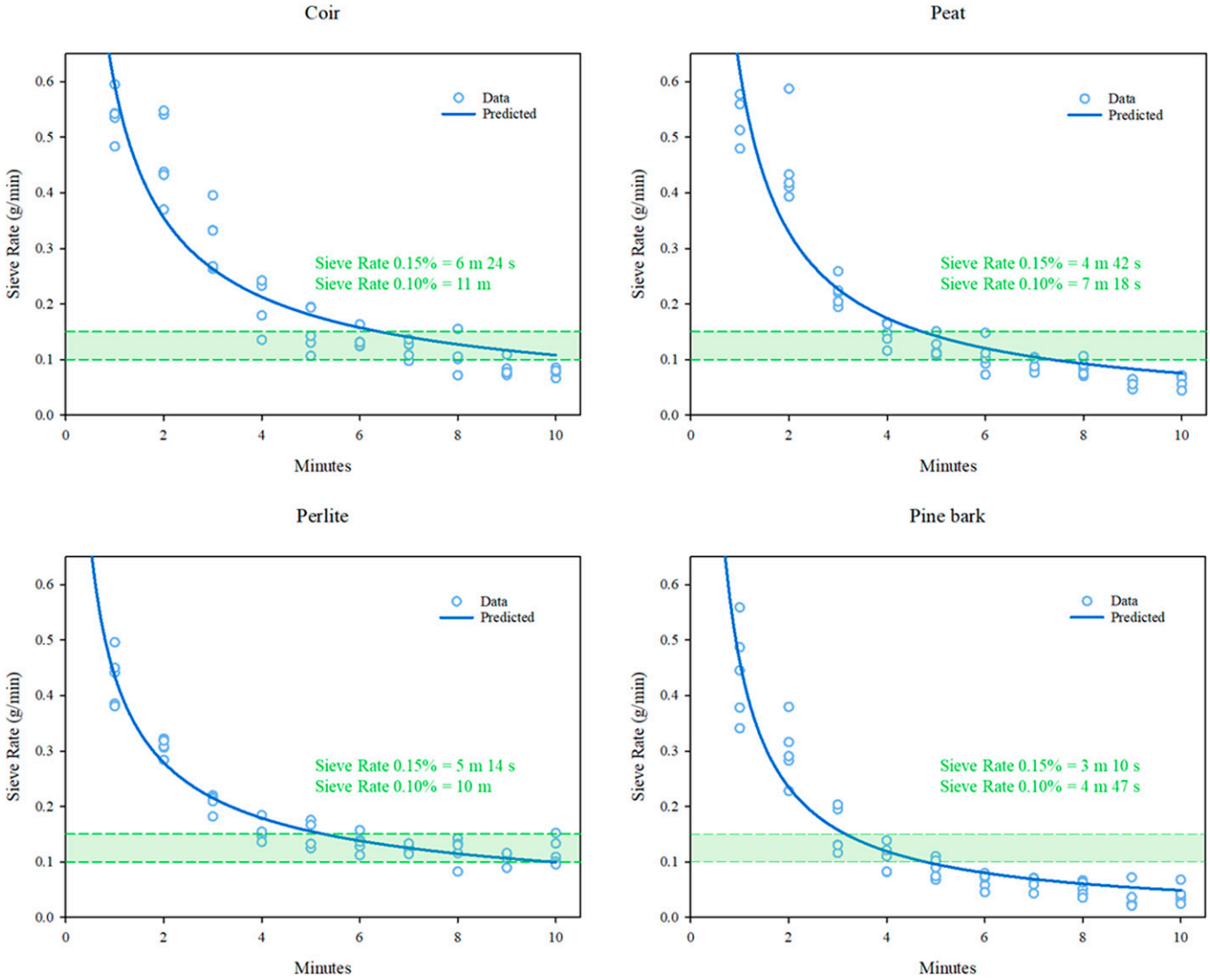

Fig. 5. Sieve rate for coir, peat, perlite, and pine bark. A sieve rate of 0.1 to 0.15 g/min may indicate the endpoint of sieving.

Materials and Methods

Sampling. The materials evaluated were sphagnum peat (BPP; Berger, Saint-Modeste, QC, Canada), pine bark (PM2; 0.32 cm screened, aged bark; Pacific Organics, Henderson, NC), coconut coir (Oldcastle Lawn and Garden, Atlanta, GA), and perlite (Krum Horticultural Perlite; Carolina Perlite Company, Gold Hill, NC). Three sample sizes were evaluated for each material. The initial sample size was selected in accordance with ISO 2591 (1988) and will be referred to as the "1×" sample size. For pine bark, the 1× sample size was 500 cm^3. For peat, coir, and perlite, the 1× sample size was 400 cm^3. Sample volumes of half (0.5×) and double (2×) the initial sample size were analyzed to determine the effect of sample size on PSA. Calculating the bulk density of the samples provided a metric to measure sample consistency. Sampling consistency was increased by bringing the moisture content of the materials up to 60% and mixing thoroughly in a large bin. Five replications were evaluated for each material at each sample size.

Before the analysis, the samples were oven-dried at 105 °C for 72 h. After drying, the samples were allowed to equilibrate to the ambient humidity and temperature for 1 week. This procedure was adopted according to observations of sample weight increases during sieve analysis.

Sieve selection. All sieves were inspected for screen damage (depressions, holes, etc.) before use and washed thoroughly. Compressed air was applied to remove particles trapped in screen apertures. To reduce the incidence of static, antistatic sheets were applied to the cylinder of the sieve before sieving. Twelve sieves plus a pan were used to evaluate materials. The sieves were arranged into two sieve nests, each containing six sieves and a pan, to accommodate the capacity of the agitator. The range of sieve sizes was determined by sieving preliminary samples. Ideally, the entire sample should be captured within the largest and smallest sieves. However, the distribution of the materials evaluated were too broad to incorporate this strategy. Instead, the largest sieve selected for each material was one that allowed more than 95% of the sample's initial mass to pass. When the largest sieve size was determined, 11 sieves of decreasing aperture size were selected in logarithmic (log_{10}) order. An additional 1× preliminary sample for each material was sieved to confirm that the maximum recommended residue within each sieve was not exceeded (ISO, 1988).

Sieve analysis. Before sieving, the weights of each sieve (including the final pan) were recorded. The nest of sieves was loaded into a Ro-Tap (Model B; W.S. Tyler, Mentor, OH) (278 oscillations and 150 taps per minute) and charged with a sample. The progress of sieving was followed by weighing the sieves after the measured interval of agitation time. Eleven agitation times were evaluated beginning at 30 s, then at 1 min, and then every additional 1 min up to 10 min. Each sieve, organized in two sieve nests, was agitated for the allotted period. Materials that passed the first sieve nest and captured in the first pan were transferred to the second nest of sieves; therefore, they were subject to being sieved longer (<1 min). Because it was not possible to determine when each particle was collected in the first pan, its influence on the data could not be quantified. After the analysis of each sample, all sieves were cleaned by compressed air and weighed again.

Data analysis. The change in weight of material within each sieve was determined as a function of time (the sieve rate of the material). The endpoint of sieving for protocols can be determined by the sieve rate of the

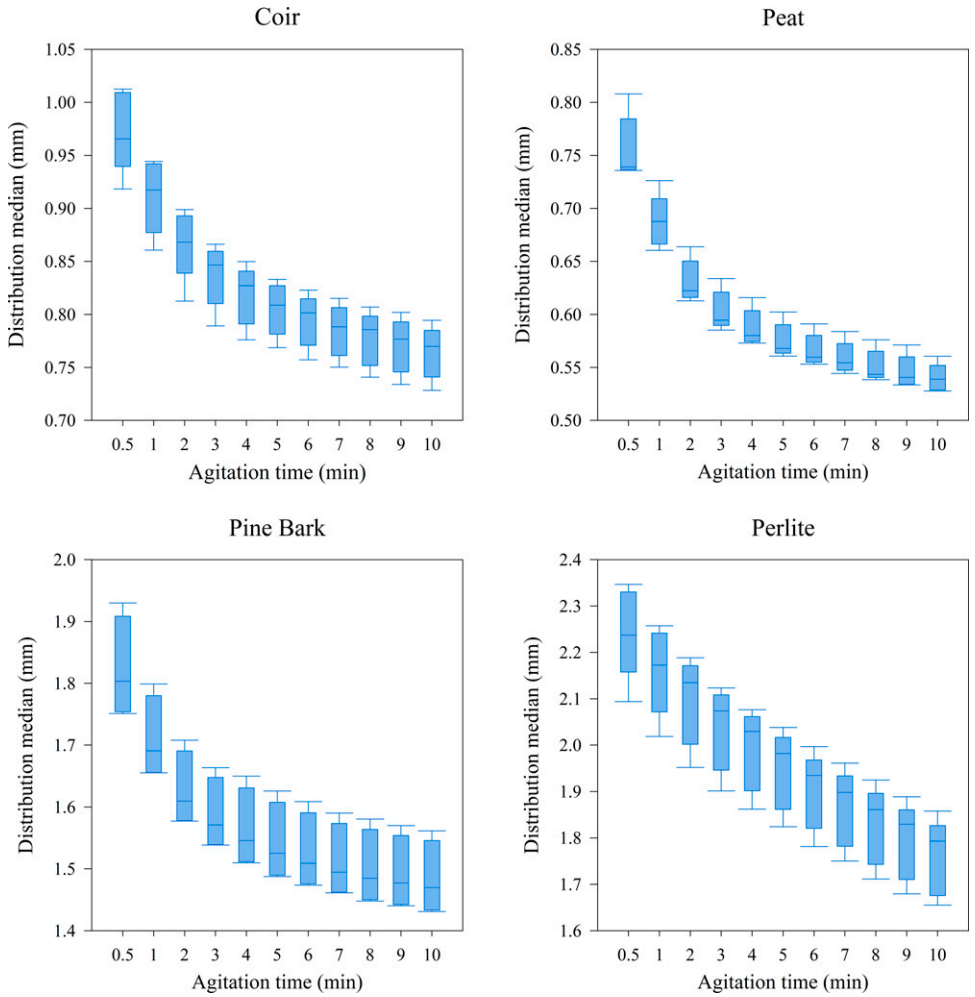

Fig. 6. Variations in distribution medians of coir, peat, perlite, and pine bark with increasing agitation times.

material. For materials with unspecified sieving endpoints, it is recommended that the quantity passing through the sieve, or through any one sieve of a nest, within 1 min is less than 0.1% of the mass of the sample for nonfriables or to be determined by a trial of friable materials (ISO, 1988). It was observed that the sieve rate varied greatly from sieve to sieve for each material tested. Therefore, the sieve rate of a singular sieve may not be indicative of the true endpoint of sieving substrates. Instead, the sieve rate of each sieve in the nest was averaged within each agitation time. The averaged sieve rate values yielded reasonable results that appeared to correspond to the endpoint of sieving for each material. The sieve rate for a material was modeled as follows:

$$SR = aT^b \quad [1]$$

where sieve rate (SR) is a function of T, which is the agitation time (in minutes), and fitting parameters a and b. From the model, the agitation time required to achieve the recommended sieve rate threshold of a 0.1% change in mass per minute was determined. However, some materials did not achieve a sieve rate of 0.1% per minute within the tested agitation times. Therefore, the agitation time required to achieve a sieve rate of 0.15% per minute was also reported. Only 1× sample sizes were evaluated to determine the sieve rate for each material.

Log-normal distribution plots of each substrate at each agitation time were graphed as differential and cumulative mass retained distributions. Mode particle size and frequency were obtained from differential mass retained distributions. Cumulative retained mass fraction data were regressed using the Rosin-Rammler distribution function, which is a Weibull cumulative distribution function (Rosin and Rammler, 1933). The Rosin-Rammler function used is as follows:

$$M_r = 1 - e^{(\frac{D_p}{a})^b} \quad [2]$$

where M_r is the cumulative retained mass as a fraction, D_p is the particle size calculated similarly to the geometric mean length assumed to be equivalent to the mean aperture size of the retaining sieve and the next larger sieve (mm), a is the Rosin-Rammler geometric mean length parameter (mm), and b is the dimensionless Rosin-Rammler skewness parameter. The particle size for any percentile of cumulative retained mass was calculated by rearranging Eq. [2] as follows:

$$D_p = a[-\log(1 - M_r)]^{\frac{1}{b}} \quad [3]$$

From Eq. [3], the particle sizes in mm corresponding to 16%, 50%, and 84% cumulative retained mass were evaluated to compare distribution medians (D_{50}) and SD (D_{84}–$D_{16}/2$), an indicator of distribution width. However, the SD includes only 68% of the distribution. Mass relative span, RS_m, is a dimensionless measure of distribution width and considers 90% of the distribution (Allais et al., 2006). The mass relative span was calculated as follows:

$$RS_m = (D_{90} - D_{10})D_{50} \quad [4]$$

where D_{10}, D_{50}, and D_{90} are the particle diameters (mm) at 10%, 50%, and 90% of the cumulative mass distribution, respectively.

Skewness and kurtosis are descriptive characteristics of distribution shape. Skewness measures the degree of asymmetry of a normal distribution curve. Its sign is indicative of whether distributions have exaggerated tails to the right (negative; skewed toward coarser particles) or the left (positive; skewed toward finer particles). Skewness was calculated based on the work by Folk (1974) describing inclusive graphic skewness (GS_i) as follows:

Table 3. Median, SD, mass relative span, skewness, and kurtosis of particle size distributions for coconut coir, Sphagnum peat, perlite, and aged pine bark substrate material at increasing agitation times.[z]

Agitation time (min)	Median (mm)	SD (mm)	Mass relative span	Skewness[y]	Kurtosis[x]
Coir					
0.5	0.97 a[w]	0.74 a	1.95 NS	+0.79 a	0.99 NS
1	0.91 b	0.69 b	1.93	+0.75 b	0.98
2	0.87 c	0.65 bc	1.93	+0.72 c	0.98
3	0.84 cd	0.63 cd	1.93	+0.70 cd	0.98
4	0.82 de	0.62 de	1.93	+0.68 de	0.98
5	0.81 d-f	0.61 d-f	1.93	+0.67 d-f	0.98
6	0.79 e-g	0.60 d-f	1.94	+0.66 d-f	0.98
7	0.78 e-g	0.59 fe	1.94	+0.66 d-f	0.98
8	0.78 fg	0.59 fe	1.94	+0.65 fg	0.98
9	0.77 fg	0.58 fe	1.94	+0.64 g	0.98
10	0.76 f	0.58 f	1.95	+0.64 g	0.99
Peat					
0.5	0.76 a	1.03 a	3.65 g	+0.71 a	1.15 g
1	0.69 b	0.99 a	3.88 f	+0.69 b	1.18 f
2	0.63 c	0.92 b	3.97 ef	+0.66 c	1.19 ef
3	0.60 d	0.90 bc	4.07 de	+0.65 cd	1.20 de
4	0.59 de	0.89 bc	4.15 cd	+0.64 de	1.21 cd
5	0.58 ef	0.89 bc	4.22 b-d	+0.64 d-f	1.22 b-d
6	0.57 e-g	0.88 bc	4.27 a-c	+0.63 d-f	1.23 a-c
7	0.56 f-h	0.88 c	4.32 ab	+0.63 d-f	1.23 ab
8	0.55 f-h	0.87 c	4.35 ab	+0.63 ef	1.24 ab
9	0.55 gh	0.87 c	4.39 a	+0.63 ef	1.24 a
10	0.54 h	0.87 c	4.41 a	+0.62 f	1.24 a
Perlite					
0.5	2.24 a	1.51 ab	1.73 h	+1.16 a	0.97 g
1	2.16 ab	1.49 b	1.77 gh	+1.14 ab	0.98 g
2	2.10 bc	1.50 ab	1.83 f-h	+1.11 a-c	0.98 fg
3	2.04 cd	1.51 ab	1.91 e-g	+1.08 b-d	0.98 e-g
4	1.99 c-e	1.53 ab	1.97 d-g	+1.07 c-e	0.99 d-g
5	1.95 d-f	1.54 ab	2.04 c-f	+1.05 d-f	0.99 c-f
6	1.90 e-g	1.55 ab	2.10 b-e	+1.03 d-g	1.00 b-e
7	1.87 f-h	1.56 ab	2.17 a-d	+1.02 e-g	1.00 b-d
8	1.83 gh	1.58 ab	2.23 a-c	+1.00 fg	1.01 a-c
9	1.79 gh	1.59 ab	2.30 ab	+0.99 fg	1.01 ab
10	1.76 h	1.60 a	2.37 a	+0.98 g	1.02 a
Pine bark					
0.5	1.82 a	2.28 a	3.33 d	+0.94 a	1.12 d
1	1.71 b	2.18 b	3.41 cd	+0.93 b	1.13 cd
2	1.63 bc	2.10 c	3.46 bc	+0.92 bc	1.13 bc
3	1.59 cd	2.06 cd	3.48 a-c	+0.91 cd	1.13 a-c
4	1.56 c-e	2.04 de	3.49 a-c	+0.91 c-e	1.13 a-c
5	1.54 c-e	2.02 d-f	3.51 a-c	+0.91 c-e	1.14 a-c
6	1.52 de	2.01 d-f	3.53 a-c	+0.91 de	1.14 a-c
7	1.51 de	2.00 ef	3.55 ab	+0.90 de	1.14 ab
8	1.50 de	1.99 ef	3.56 ab	+0.90 de	1.14 ab
9	1.49 e	1.98 ef	3.57 ab	+0.90 e	1.14 ab
10	1.48 e	1.98 f	3.58 a	+0.90 e	1.15 a

[z]Samples agitated with a Ro-Tap (278 oscillations and 150 taps per minute).

[y]Skewness was calculated from the work of Folk (1974), who described inclusive graphic skewness (GSi) calculated as follows: $GS_i = \frac{D_{16} + D_{84} - 2D_{50}}{2(D_{84} - D_{16})} + \frac{D_5 + D_{95} - 2D_{50}}{2(D_{95} - D_5)}$ where D_5, D_{16}, D_{50}, D_{84}, and D_{95} are the particle diameters (mm) at 5%, 16%, 50%, 84%, and 95% cumulative mass retained, respectively.

[x]Kurtosis was calculated as follows: $K_g = \frac{D_{95} - D_5}{2.44(D_{75} - D_{25})}$ where D_{25} and D_{75} are the particle diameters (mm) at 25% and 75% cumulative mass retained, respectively.

[w]Means within material with different letters in each column are significantly different ($\alpha = 0.05$). Means designated with the same letters or "NS" (not significant) are not significantly differently.

$$GS_i = \frac{D_{16} + D_{84} - 2D_{50}}{2(D_{84} - D_{16})} + \frac{D_5 + D_{95} - 2D_{50}}{2(D_{95} - D_5)} \quad [5]$$

where D_5 and D_{95} are the particle diameters (mm) at 5% and 95% cumulative mass retained, respectively. The interval between D_5 and D_{95} should be exactly 2.44-times the interval between D_{25} and D_{75} on a normal distribution curve. Kurtosis represents the departure of a distribution from normality (Folk, 1974). Kurtosis (K_g) was calculated as follows:

$$K_g = \frac{D_{95} - D_5}{2.44(D_{75} - D_{25})} \quad [6]$$

where D_{25} and D_{75} are the particle diameters (mm) at 25% and 75% cumulative mass retained, respectively.

A nonlinear regression procedure (proc nlin) was used to fit all sieve rate data and cumulative distributions (SAS 9.4; SAS, Cary, NC). The distribution median, SD, mass relative span, skewness, and kurtosis means comparisons were accomplished using a generalized linear model procedure (PROC GLM) and analyzed by substrate to evaluate the effects of agitation time and sample size. All significances were set at $\alpha = 0.05$.

Results

Size distributions. The most frequent agitation time used in previously reported literature was 5 min. Therefore, the mass fraction retained on each sieve after 5 min of agitation was graphed for each material of the 1× sample size for visualization in a traditional format (differential distribution) and the format used for analytical comparisons (cumulative distribution) (Fig. 4). Coir, perlite, and pine bark followed a log-normal distribution, with primary modes found at 0.71 mm for coir and 2.8 mm for perlite and pine bark. The distribution of peat could be considered trimodal, with modes located at 2.8, 0.355, and <0.125 mm, although no mode contained a fraction larger than 11% of the sample's mass. Cumulative distribution curves for each material showed positive skewness, apparent from the exaggerated left tails that are indicative of excess coarse particles (Folk, 1974). With broad distributions and varying fractions of material captured within each test sieve, it was difficult to justify the endpoint of sieving by any one sieve. Instead, the sieve rate of each sieve was averaged to distribute the influence of determining the endpoint of sieving to all sieves.

Sieve rate analysis. The process of sieving consists of two regions, the initial region and the near-mesh particle size region. The initial region is characterized by a rapid change in the weight of material in each sieve as particles with dimensions much smaller than aperture sizes readily pass. The initial phase of sieving substrate materials can be visualized within the first 3 to 4 min of agitation (Fig. 5). Rapid separation of substrate particles occurred during this phase. On average, 95% of the samples were sorted during the first 30 s. The near-mesh particle size region of the curves expresses the slower rate at which particles with dimensions slightly smaller than the sieve aperture pass. It is suggested that the endpoint of the sieving process should be reached when the rate of change within 1 min is less than 0.1% of the initial sample's mass for nonfriable materials (ISO, 1988). Pine bark required the shortest agitation time to reach this threshold at 4 min and 47 s, followed by peat at 7 min and 18 s The agitation time required for perlite and coir extended to the limit of and beyond the tested agitation times at 10 min and 11 min, respectively. These prolonged agitation periods could be indicative of the friable nature of the tested materials, particularly perlite and coir. If the sieve rate threshold was increased from 0.1% per minute to 0.15% per minute, then the agitation time required to

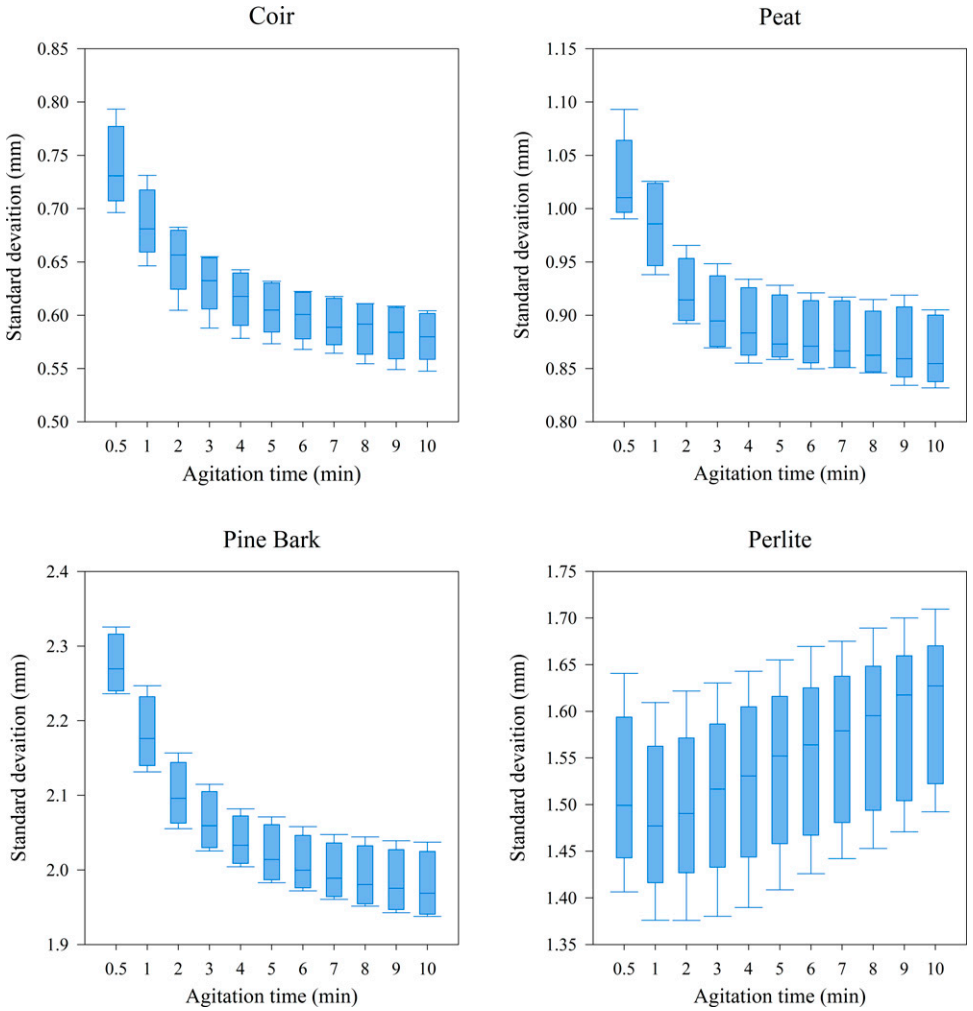

Fig. 7. Variations in distribution SD of coir, peat, perlite, and pine bark with increasing agitation times.

reach the endpoint of sieving would be 3 min and 10 s for pine bark, 4 min and 42 s for peat, 5 min and 14 s for perlite, and 6 min and 24 s for coir.

Distribution median, SD, and mass relative span. The mean separation of distribution medians, SD, and relative deviations indicated significant differences in distribution characteristics by agitation time (Table 3). As agitation time increased, the distribution median for each material decreased (Fig. 6). The difference in medians from 0.5 to 10 min of agitation time was 0.21 mm for coir. However, no differences were observed between 5 and 10 min of agitation time for coir. Similar trends were observed for median values of peat, perlite, and pine bark. No differences in median values were observed when agitation time extended beyond 4 min for pine bark and 7 min for peat and perlite.

As agitation time increased, the SD decreased for all materials except for perlite (Fig. 7). In contrast, the mass relative span for peat, perlite, and pine bark increased with increasing agitation time (Fig. 8). A distribution's SD considers the central 67% of the distribution, whereas the mass relative span considers 80% of the distribution. For peat, perlite, and pine bark, increasing the agitation time resulted in a tighter central distribution with more expansive tails. Increasing agitation time decreased coir's SD, but it did not affect the mass relative span. It is plausible that the decrease in deviation was offset by an increase in the more expansive regions considered by the mass relative span.

Skewness and kurtosis. All materials yielded strongly positive-skewed distributions; the values for each material exceeded +0.30 (Folk, 1974). The mean separation of skewness followed a grouping trend similar to that of distribution medians. Perlite and pine bark distributions were more strongly skewed than those of coir and peat, indicative of their coarse texture and use as a component to increase air-filled porosity (Bilderback et al., 2005; Verdonck et al., 1983). The mean separation of kurtosis followed a grouping trend similar to that of mass relative span. Coir and perlite distributions are classified as "mesokurtic," because kurtosis was within 0.90 and 1.11, indicating the two materials followed a normal distribution (Folk, 1974). Peat and pine bark are classified as "leptokurtic" (1.11–1.50), signifying these distributions contained a larger spread in the tails than the in the central part. Therefore, the distributions' shapes for coir and perlite can be classified as "strongly fine-skewed mesokurtic" and "strongly fine-skewed leptokurtic" for peat and pine bark.

Sample size. Sample sizes vary widely in previously reported literature (Table 1). The most frequently used volume sizes (if reported) are closer to the 0.5× sample size determined from ISO standards. A concern with undersized sampling is the inability to express the true characteristics of the material. However, oversized sampling may induce the sieve blinding effect and result in erroneous distributions. To induce sieve blinding, the 2× sample sizes were selected to double the recommended volume of charge (ISO, 1988). As a result, the volume of residue on at least one sieve exceeded the recommend maximum by more than 100%. Despite the concern with undersized and oversized sampling, the distributions of 0.5× and 2× sample sizes for coir, peat, perlite, and pine bark showed small and few differences (Table 4). Distribution medians were larger for 2× sample sizes of coir and pine bark, with differences of 0.02 and 0.08 mm, respectively. However, the scale at which PSA is observed for substrates is unlikely to consider differences less than 0.1 mm to be significant. No interactions between sample size and agitation time were observed, indicating distributions responded similarly to changes

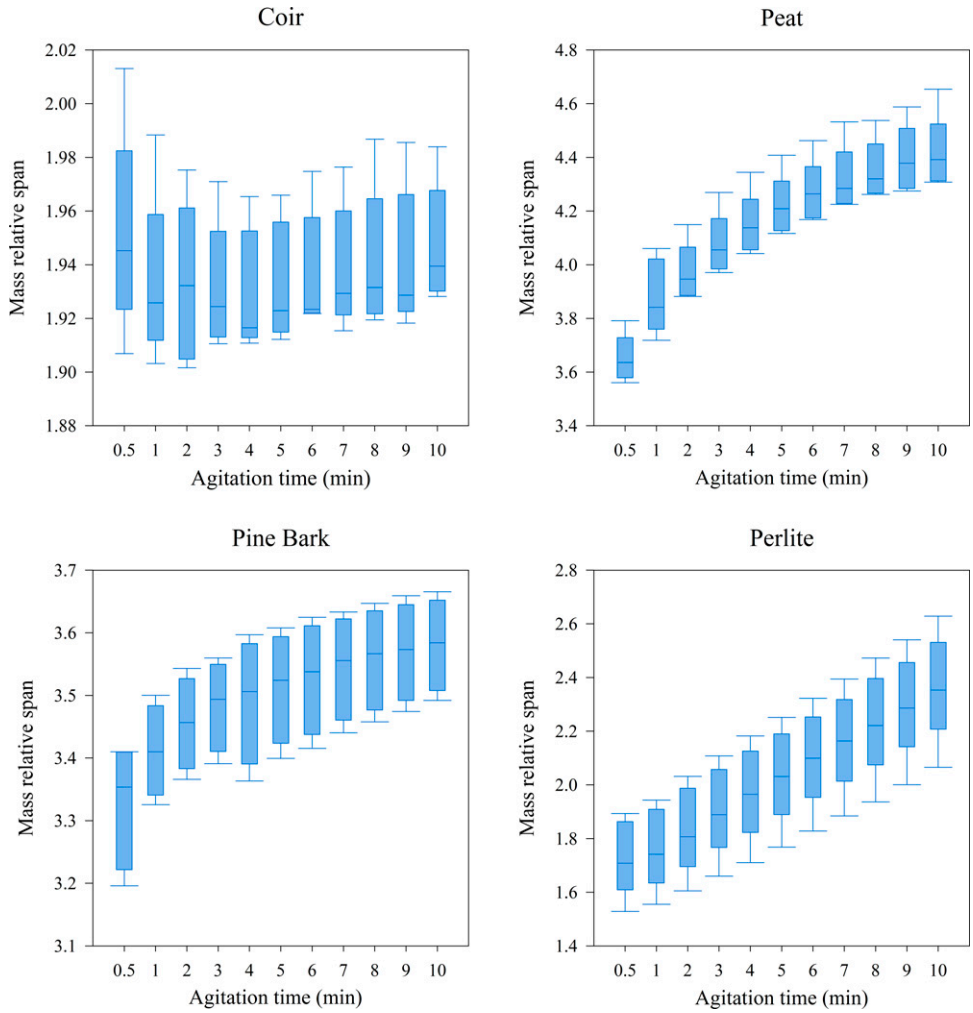

Fig. 8. Variations in mass relative span of coir, peat, perlite, and pine bark with increasing agitation times.

Table 4. Median, SD, mass relative span, skewness, and kurtosis of particle size distributions for coir, peat, perlite, and pine bark at half and double the recommended sample sizes.[z]

Material	Sample size[y]	Median (mm)	SD (mm)	Mass relative span	Skewness[x]	Kurtosis[w]
Coir	0.5x	0.69 b[v]	0.60 b	2.14 b	+0.57 b	1.00 NS
	2x	0.71 a	0.57 a	2.21 a	+0.59 a	1.00
Peat	0.5x	0.59 NS	0.96 NS	4.47 a	+0.66 NS	1.25 a
	2x	0.60	0.92	4.23 b	+0.66	1.22 b
Perlite	0.5x	1.42 NS	1.63 NS	3.04 NS	+0.90 NS	1.09 NS
	2x	1.40	1.60	3.03	+0.89	1.08
Pine bark	0.5x	1.40 b	2.08 a	4.12 a	+0.89 NS	1.21 a
	2x	1.48 a	1.97 b	3.57 b	+0.90	1.14 b

[z]Recommended sample size according to the International Standard Organization.
[y]A sample size of 0.5× = 200 cm^3 for coir, peat, and perlite and 250 cm^3 for pine bark. A sample size of 2× = 800 cm^3 for coir, peat, and perlite and 1000 cm^3 for pine bark.
[x]Skewness was calculated from the work of Folk (1974), who described inclusive graphic skewness (*GSi*) calculated as follows: $GS_i = \frac{D_{16} + D_{84} - 2D_{50}}{2(D_{84} - D_{16})} + \frac{D_5 + D_{95} - 2D_{50}}{2(D_{95} - D_5)}$ where D_5, D_{16}, D_{50}, D_{84}, and D_{95} are the particle diameters (mm) at 5%, 16%, 50%, 84%, and 95% cumulative mass retained, respectively.
[w]Kurtosis was calculated as follows: $K_g = \frac{D_{95} - D_5}{2.44(D_{75} - D_{25})}$ where D_{25} and D_{75} are the particle diameters (mm) at 25% and 75% cumulative mass retained, respectively.
[v]Means within material with different letters in each column are significantly different ($\alpha = 0.05$). Means designated with the same letters or "NS" (not significant) are not significantly differently.

in agitation time despite a vast difference in sample volume.

Conclusion

The sieve rate of each substrate component varied. These differences could be attributed to particle shape, friability, or the inherent sievability (how easily particles disperse and sort) of the materials. Despite the observed differences, these data suggest the endpoint of sieving for the evaluated materials is within a relatively narrow range of agitation times (4–7 min). The Rosin-Rammler equation fit well with the size distribution data for each substrate component (PseaudoR >0.997). The parameters evaluated descriptively characterized PSD location and shape to discern and quantify notable differences. Increasing agitation time resulted in a decrease in the median, SD, and skewness. However, few differences were observed between 5 and 10 min of agitation time, supporting the results obtained from the sieve rate analysis. Sample size did not affect PSD to a degree considered significant at the scale at which most substrate PSA is conducted. However, the manner in which a material is sampled could influence PSA and a sampling protocol should be considered in future work. For precise results, agitation times and sample sizes should be specified for each material or collectively for all materials to ensure consistency and to allow comparisons to be made between results.

Sieving blends of materials, and not sole components, could pose several challenges. First, the sieve rate of each component in the blend may vary. In this instance, agitation time should be selected according to the component with the longest agitation time or determined by a quick sieve rate analysis. Consideration should also be given to the friability of each component. Second, mass-weighted distributions of substrate blends could be affected by the different densities of each component. For example, the bulk density of perlite can be different from that of pine bark or sand. Specifically, these differences in density are reflective of the materials' particle envelope density (a particle's mass divided by its volume where internal pores are included). Ideally, PSA for each substrate component should be determine before blending. If this is not possible, then PSA may be more accurately weighted by volume rather than mass. To consider the effects of substrate blends and alternative components, additional research is warranted.

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