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Effect of particle length to width ratio on sieving accuracy and precision

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ABSTRACT

The physical, hydrological, and physico-chemical properties of horticultural substrates are influenced by particle shape and size. Sieve analysis is the predominate method utilized to characterize the particle size distribution of horticultural substrates. However, the effect of particle length on sieve analysis results have only been speculated. Laser cut particles with eight different length to width (L:W) ratios were sorted by sieves for agitation times ranging from 1 min to 5 min. To quantify the effect of L:W ratio and agitation time, the means (mid-point) and standard deviations of particle distributions were compared. Particles with a 1:1 L:W ratio were the most accurately sorted particles, containing midpoints most similar to true sieve size. As particle length increased, distribution midpoints and standard deviation increased. Elongated particles, 2:1 L:W ratio and greater, may cause the particle size distribution to skew positively. Increasing agitation time influences the probability of a particle and open sieve aperture converging in an orientation which allows it passage and can improve sieve accuracy and precision. By improving the consistency of sieving protocols, the accuracy of sieve analysis could potentially be improved. However, alternative instruments should be evaluated to improve the characterization of horticultural substrates. If, in the future, the characteristics of elongated or complex-shaped particles are desired, it may prove more beneficial to refine engineering practices than rely on sieving to precisely sort and isolate them.

1. Introduction

The effects of particle size on the properties of aggregate materials have been a focal point for a diversity of research fields from the tabletization of pharmaceutical drugs to the flowability of biomass materials for biofuels [1–3]. Equivalently, horticultural container substrates can be classified as aggregate materials whose physical and hydrological characteristics are affected by particle size [4]. The physical properties of substrates (e.g., bulk density and porosity) are, in major part, consequences of the particle size distribution (PSD) of the material [5–7]. Additionally, differences in the hydrological properties of substrates, such as water holding capacity and hydraulic conductivity, are mostly defined by the different pore characteristics imparted by particle size and arrangement [6–9]. For these reasons, particle size analysis (PSA) is widely used as a metric to indicate differences between materials or, for some researchers, included in predictive models to derive a substrate's physical and hydrological properties [10].

Substrate particle shape and size influence plant rooting environments. As plant production progresses more toward precisely engineered growing environments, our ability to engineer rooting environments with specific properties must also progress. The capacity to develop substrates of more consistent and predictable properties requires the ability to select for specific particle dimensions.

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 [4,10]. This method of characterization is the only method available to physically separate a material solely based on particle size [10,11]. However, the exact means by which irregularly-shaped organic particles interact with open apertures on a screen is not fully understood.

Sieves allow the passage of a particle by the second smallest dimension. This dimension is generally referred to as a particle's width. From this point forward, a particle's width will be referred to as the particle's “true sieve size” as it is impossible for the particle to pass through an aperture of smaller dimensions. However, the probability of a particle being fractioned to its true sieve size is thought to be influenced by additional particle dimensions [10–14]. The probability of a particle being retained 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 [12,13,15]. The proper orientation for passage is relative to particle shape and length. Shapes and sizes which do not obtain the proper orientation may rest on screen sizes larger than its true sieve size, resulting in an apparent coarsening of the particle size distribution [12].

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The complex interactions between particles, sieves, and shaking devices have led researchers to speculate differently as to what sieve analysis characterizes, particularly as it applies to particle length. Fernlund [13] noted that the least cross-sectional dimension (width and height) of a particle is most important and that the longest dimension usually has little effect. Allen [11] states that particle length does not affect the passage of particles unless they are excessively elongated while others simply note that elongated particles may necessitate increased agitation times in order to be sorted to their true sieve size [15]. Syvitski [12] considered sieve analysis a 2.5-dimensional measurement of particles and that the best values for describing particle retention in a sieve may be the length and its area. These mixed hypotheses highlight the complexity of particle/sieve interactions and the difficulties in obtaining data to illuminate particle length's influence.

The potential for particle length to affect sieve analysis can vary based on the physical nature of the material. Rocks and pharmaceutical powders would have more consistent, almost spherical dimensions; so length would have little influence on the sorting of these materials. Conversely, horticultural substrate components like perlite and wood fiber vary greatly from one another in particle length to width ratio (L:W). Other components, such as peat and pine bark, may contain a diverse range of particle shapes and sizes. Considering the innumerable particle shapes and sizes in substrate components, any investigation regarding sieve analysis' ability to measure and accurately sort particles in horticultural substrates should include a range of particle sizes and lengths.

The objective of this study was to evaluate the ability of sieve analysis to measure and sort particles of various widths and lengths.

2. Materials and methods

Acrylic particles were laser cut and etched to create a synthetic, multidimentional material. Durable and easily recoverable, these particles had no size reduction during multiple analyses. Acrylic sheets (Inventables, Inc., Chicago, IL) of 2-mm, 3-mm, and 6-mm thickness were cut using a laser cutter (Zing 24, Epilog Laser, Golden, CO). Three particle classes were developed based on each height and width: 2-mm class, 3-mm class, and 6-mm class (Fig. 1). Eight L:W ratios ranging from 1:1 to 8:1 were cut for each particle class. Thus, the smallest particles evaluated were 2 × 2 × 2 mm (1:1) cubes and the largest were 6 × 6 × 48 mm (8:1) rectangles (Table 1). The height between consecutive sieves, 50 mm, limited the evaluation of higher L:W ratios. Each particle had its dimensions etched onto one surface to more effectively sort and count samples by particle length.

The 2-mm, 3-mm, and 6-mm particle classes were evaluated separately. Each sample consisted of 800 total particles, 100 particles of each L:W ratio. The sieve sizes used were 19, 16, 12.5, 9.5, 6.3, 5.6, 4.75, 4, 3.35, 2.8, 2.36, and 2 mm. Square-holed, woven-wire sieve sizes were selected to give each size class approximately 5 sieves in which to be captured (evaluated by preliminary hand sieving). Since only 6 sieves (plus a pan) could be agitated at a time, the series of sieves was split into two sieve nests. Samples were evenly dispersed onto the largest sieve of the coarsest sieve nest. Following initial sorting, the contents captured in the pan were transferred to the next sieve nest and the analysis continued.

Table 1
Particle dimensions evaluated by sieve analysis.

L:W[z]	Particle class 2-mm	 3-mm	 6-mm
1:1	2 × 2 × 2[y]	3 × 3 × 3	6 × 6 × 6
2:1	2 × 2 × 4	3 × 3 × 6	6 × 6 × 12
3:1	2 × 2 × 6	3 × 3 × 9	6 × 6 × 18
4:1	2 × 2 × 8	3 × 3 × 12	6 × 6 × 24
5:1	2 × 2 × 10	3 × 3 × 15	6 × 6 × 30
6:1	2 × 2 × 12	3 × 3 × 18	6 × 6 × 36
7:1	2 × 2 × 14	3 × 3 × 21	6 × 6 × 42
8:1	2 × 2 × 16	3 × 3 × 24	6 × 6 × 48

[z] Length to width ratio.
[y] Height × Width × Length. All dimensions measured in millimeters.

Although vibration instruments are commonly used to agitate samples, in horticultural research in the US, the majority of studies utilize Ro-Tap Shakers which implement circular and tapping movements simultaneously to sort samples [16–18]. Due to this precedence, the samples were agitated using a Ro-Tap (Model B, W.S. Tyler, Mentor, OH) (278 oscillations and 150 taps per minute). The most commonly utilized agitation times range from 3 min to 5 min for horticultural materials, though agitation times up to 20 min have been reported [18,19]. In another sieve rate analysis study, the sorting of horticultural substrates by sieves occurred rapidly with little to no sorting observed after 5 mins of agitation [19]. To assess the effect of agitation time from the initial sorting phase to completion, the samples were agitated for 1, 2, 3, 4, and 5 min. Each particle class at each agitation time was replicated 3 times. After each run, the fractioned sample was hand-sorted and the number of particles by L:W ratio was recorded for each sieve (Fig. 2).

Traditionally in horticultural science, sieve analysis data are reported as histograms showing differential distributions of the fraction retained on each sieve. Data collected from the run depicted in Fig. 2 and two additional replications are graphically displayed in this traditional format (Fig. 3). This format allows practitioners to quickly determine whether the materials are within their quality assurance specifications. Alternatively, the same data can be displayed as a cumulative passing distribution. This format allows the distribution to be described with two additional terms, the midpoint of the curve and the deviation of the distribution around that midpoint.

Following this format, a logistic model, Eq. (1), within PROC NLIN (SAS 9.4, SAS, Cary, NC) was used to fit separate cumulative distribution

Fig. 1. Acrylic sheets were cut into three size classes of particles: 2-mm (top left), 3-mm (top right), and 6-mm (bottom center). Eight length to width ratio particles were cut in each size class from 1:1 to 8:1. The sizes were etched onto each particle for ease of identification and separation during analysis.

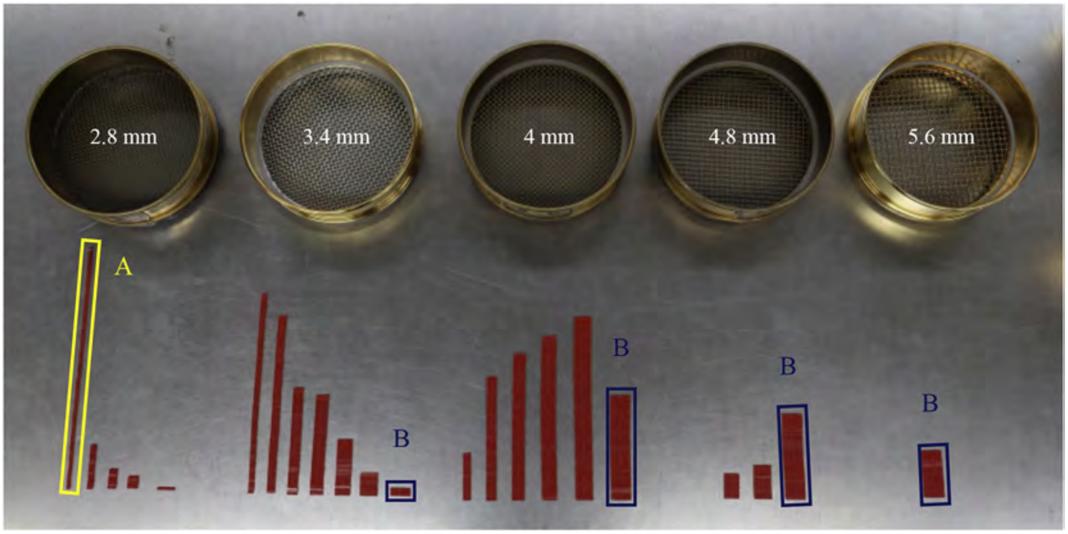

Fig. 2. A sample comprised of 800 particles, 100 particles each of the eight length to width (L:W) ratios, were distributed across five sieves following 5 min of agitation. Each of the 800 particles has a width and height of 3 mm. All 1:1 ratio particles (A) were captured in the 2.8-mm sieve. In contrast, the 8:1 ratio particles (B) were distributed across 4 different sieves with the largest fraction (43%) retained in the 4-mm sieve.

curves for each L:W ratio, agitation time, and run combination.

$$Passing = \frac{100}{1 + \exp\left(-\frac{\text{Sieve Size} - K}{S}\right)} \tag{1}$$

The variable, "*K*" represents the mid-point of the distribution or the interpolated sieve size that would retain 50% of the particles (depicted in Fig. 3). From this point forward, the "mid-point" of the distribution will be discussed alternatively to "*K*". The variable, "*S*" describes the breadth of the distribution and is proportional to the standard deviation of the distribution. The standard deviation (σ) for each model was calculated from Eq. (2).

$$\sigma = (S \text{ x } \pi)/\sqrt{3} \tag{2}$$

In the cumulative distribution in Fig. 3, the standard deviation can be visualized as points 13.6% ($-\sigma$) and 86.4% ($+\sigma$) on the y-axis. All mid-point and deviation values were subjected to PROC GLM. Means separated by LSD ($\alpha = 0.05$).

3. Results and discussion

3.1. Sieve analysis accuracy

The mid-point of a distribution is a valuable indicator of sieve analysis' ability to sort particles to their true sieve size. The more efficient the sorting process, the closer the midpoint is to the width of the particles. For example, the 3 × 3 × 3 mm particles were all captured on one sieve just below 3 mm in diameter, with a resulting midpoint of 3.02 (Fig. 3). However, the 3 × 3 × 24 mm particles were spread out over five sieves, four of which were larger than 3 mm in diameter. Therefore, the midpoint was higher at 4.92 mm. Distribution mid-points within each particle class were affected by particle L:W ratio ($p \le 0.0001$), agitation time ($p \le 0.0001$), and their interaction ($p \le 0.0001$) for all particle classes (Fig. 4). The significant interaction between L:W ratio and agitation time indicated that particles with different L:W ratios respond dissimilarly to changes in agitation time.

Distributions of 1:1 ratio particles had the lowest mid-points, closest to their respective true sieve size (width). Also, any change in sieve's ability to sort and accurately measure 1:1 ratio particles by increasing agitation time were negligible (Fig. 4). As L:W ratio increased, the distribution mid-point also increased and agitation time's capacity to shift the mid-point became more pronounced. Increasing agitation time resulted in lower distribution mid-points for elongated particles, drawing the distributions closer to the true sieve size within each respective particle class.

The accuracy of sieve analysis to measure materials may be estimated by isolating the effect of L:W ratio and agitation time. With agitation time fixed, the mid-points of each L:W ratio within their respective particle class were compared (Table 2). The midpoint skew was calculated as the change in the mid-point from 1:1 ratio particles within each particle class. For example, the 2-mm class midpoints of 2:1 was 2.34 verses 2.20 for 1:1 with a skew (relative midpoint deviation) of 6% (Table 2). Overall, as particle length increased, the relative skew of the distribution mid-point increased. As particle width (class) increased, the relative skew increased for 8:1 particles from 47% to 99% for 2-mm and 6-mm class, respectively.

This affect could be a result of an interaction between particle size and the force applied by the agitation device. The orientation a particle must achieve in order to pass a sieve screen is dependent upon its L:W ratio and form (the latter supported by Fernlund [13]). As L:W ratio increases, greater angles relative to the plane of the screen are needed to allow passage. As particle volume or mass increases relative to L:W ratio, more force must be applied for particles to approach angles which would allow passage. However, the forces applied by mechanical agitation devices, such as a Ro-Tap, are constant. Thus, the disproportional effect observed within the same L:W ratio but different particle size could be a consequence of the disproportional force applied by the agitation device. With this considered, the accuracy of sieve analysis to sort a homogeneous material is relative to the material's L:W ratio, particle mass, and force applied by the agitation device.

Combining all L:W ratios within a class, the mid-points at each agitation time within were compared (Table 3). These combined L:W ratios could be considered values of a heterogeneous sample. As agitation time increased, the mid-point decreased for each particle class. This suggests increasing agitation time improves the probability of a particle and an open aperture converging. Additionally, the probability of an elongated particle achieving an orientation which allows it passage could also improve. In essence, increasing agitation time allows greater opportunities for particles to be sorted accurately. However, the agitation times theoretically required to accurately sort elongated particles may

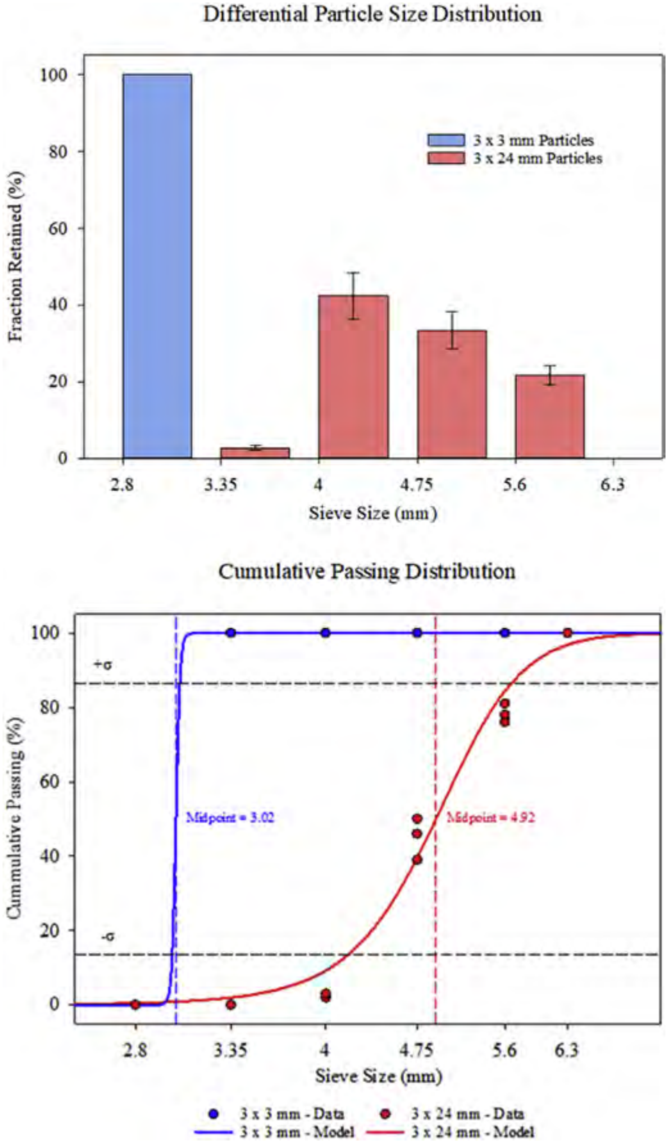

Fig. 3. Differential particle size distribution (top graph) and modeled cumulative passing distribution (bottom graph) of 3-mm particles with a length to width ratio of 1:1 and 8:1.

result in the attrition of the material, particularly friable organics. Therefore, the coarsening effect of elongated particles within a heterogeneous material may be diminished by increasing agitation time but likely not eliminated.

Table 2
Particle length to width ratio (L:W) affects the particle size distribution midpoint of samples comprised of 2-mm, 3-mm, or 6-mm wide particles.

	Particle class (width)					
	2-mm[z]		3-mm		6-mm	
L:W	Mid-point	Skew[y]	Mid-point	Skew	Mid-point	Skew
1:1	2.20h[x]	–	3.15 h	–	6.20 h	–
2:1	2.34 g	6%	3.61 g	15%	6.50 g	5%
3:1	2.56f	16%	3.97f	26%	8.70f	18%
4:1	2.69e	22%	4.18e	32%	8.96e	44%
5:1	2.82d	28%	4.33d	37%	9.53d	54%
6:1	2.94c	34%	4.57c	45%	10.11c	63%
7:1	3.10b	41%	4.83b	53%	11.20b	81%
8:1	3.24a	47%	5.41a	71%	12.33a	99%

[z] Means within a column and row are averaged across five agitation times (1 min – 5 min). Samples agitated by a Rotap (278 oscillations and 150 taps/min).

[y] Skew defined as the positive or negative shift in the distribution midpoint, expressed as a percentage, from 1:1 ratio midpoints within each particle classes.

[x] All means reported in millimeters. Any two means within a column not followed by the same letter are significantly different at p ≤ 0.05.

Table 3
Agitation time affects the particle size distribution midpoint of samples comprised of 2-mm, 3-mm, or 6-mm wide particles.

	Particle class (width)		
Agitation time	2-mm[z]	3-mm	6-mm
1 min[y]	3.12a[x]	4.81a	10.91a
2 min	2.88b	4.53b	10.38b
3 min	2.78c	4.36c	10.28b
4 min	2.71d	4.23d	10.28b
5 min	2.59e	4.14e	10.00c

[z] Samples within each particle class are comprised of 800 particles, 100 particles from each of eight length to width ratios (1:1–8:1).

[y] A RoTap (278 oscillations and 150 taps/min) was used to agitate all samples.

[x] All means reported are in millimeters. Any two means within a column not followed by the same letter are significantly different at $p \leq 0.05$.

3.2. Sieve analysis precision

As the mid-point of a distribution can estimate the accuracy of sieve analysis to characterize particle size, the standard deviation of the distribution might be used to estimate the precision in which particles of differing sizes can be sorted. A small standard deviation indicates the breadth of the PSD is narrow and, hence, has a greater probability of being sorted and recovered within fewer sieves. In order to calculate reasonable standard deviations, it was necessary for sieves to be selected in a logarithmic, evenly-spaced order. The sieves chosen for this study fit these criteria for the 2-mm and 3-mm classes but not for the

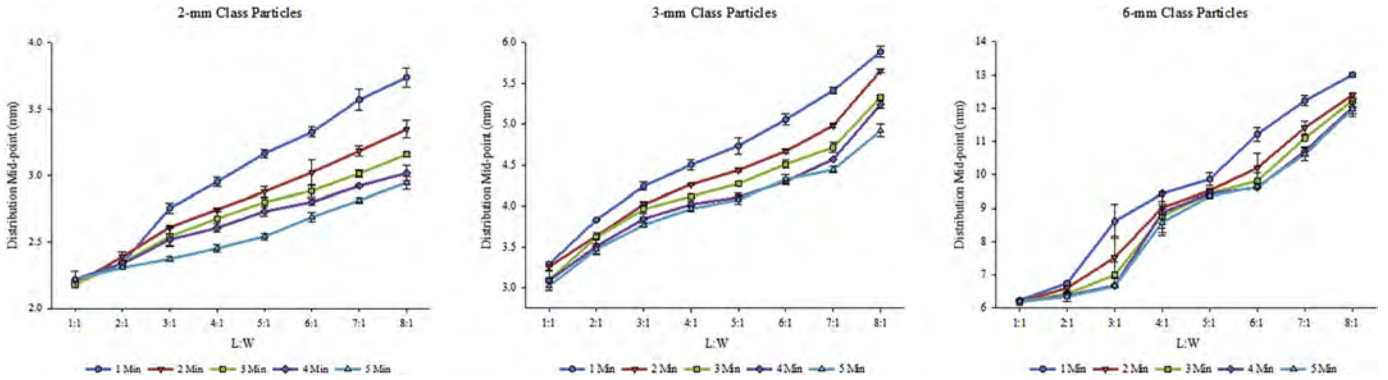

Fig. 4. Changes in distribution mid-point as affected by particle length to width ratio (L:W) and agitation time. Particle width and height were equal and determined a particle's classification (i.e. 2 × 2 mm (height x width) particles comprised the 2-mm Class).

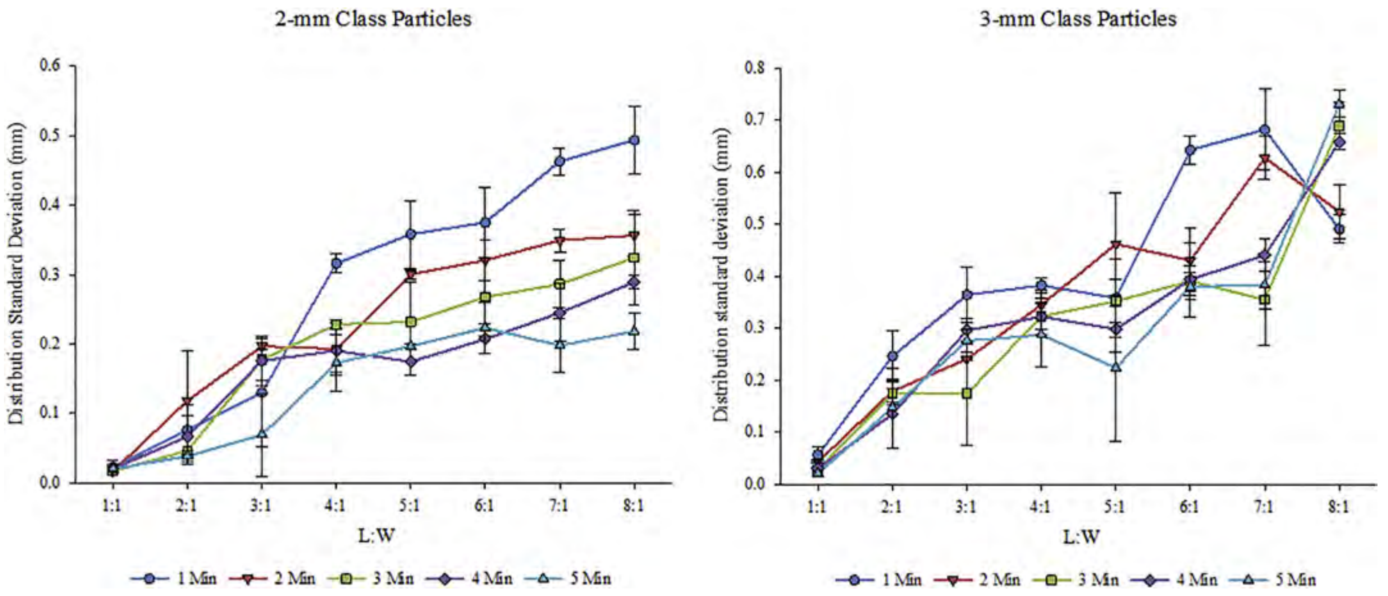

Fig. 5. Changes in the standard deviations of distributions as affected by particle length to width ratio (L:W) and agitation time. Particle width and height were equal and determined a particle's classification (i.e. 2 × 2 mm (height x width) particles comprised the 2-mm class).

6-mm class. For this reason, the standard deviations of the 6-mm class were excluded.

In the 2-mm and 3-mm classes, the standard deviation was affected by L:W ratio ($p \leq 0.0001$), agitation time ($p \leq 0.0001$), and their interaction ($p \leq 0.0001$). The interaction between L:W ratio and agitation time affected standard deviation similarly to distribution mid-points (Fig. 5). Distributions of 1:1 ratio particles had the lowest standard deviation and were sorted most precisely with agitation time having little effect. As L:W ratio increased, standard deviation increased and agitation time's capacity to affect the standard deviation was more pronounced.

To illustrate the probability of recovering particles of specific lengths following sieve analysis, the standard deviations of each L:W ratio were compared within particle class (Table 4). As L:W ratio increased, the standard deviation also increased. This implies that the more elongated a particle is, the higher its probability of being retained in multiple sieves. This incidence would decrease the probability of isolating and recovering elongated particles if a specific size is desired. Furthermore, this tendency may have implications for our interpretations of sieve analysis results. Following previous examples, the 8:1 ratio particles of the 3-mm class were agitated for 5 mins. Visually displayed in Fig. 2, sorting these particles revealed a distribution which span across four sieves. Given this distribution without cognizance of the sample's true composition, a traditional interpretation of the PSA results would conclude that this sample, made of identical particles, was composed of four, distinct particle sizes. As particle size influences the physical properties of aggregate materials, these four distinct sizes could, theoretically, contribute four different characteristics. These two interpretations would be false. For sieves to precisely sort particles, the L:W ratio must be near 1:1. As particle L:W ratio increases, the validity of traditional interpretations of PSA could diminish.

Comparing standard deviations of each agitation time (L:W ratio fixed) could delineate the ability of sieve analysis to precisely sort a heterogenous material. The standard deviation of particle distributions decreased as agitation time increased (Table 5). This suggests materials comprised of an assortment of L:W ratios could be more precisely characterized by increasing the agitation time. However, there may be diminishing returns for improved sieve analysis precision by increasing agitation time. No differences in the standard deviations were observed between 3 min and 5 min in the 3-mm class of particles. While the mid-point of these distributions changed significantly by increasing agitation time, the standard deviation did not. This suggests that these distributions were parallel to one another along the x-axis and that relatively small increases in agitation time were unsuccessful in reducing the breadth of their PSD.

Table 4
Particle length to width ratio (L:W) affects the standard deviation of particle size distributions.

	Particle class (width)		
L:W	2-mm[z]	3-mm	6-mm
1:1	0.020g[y]	0.036 g	--[x]
2:1	0.069f	0.192f	–
3:1	0.151e	0.281e	–
4:1	0.219d	0.332d	–
5:1	0.252c	0.356d	–
6:1	0.279c	0.448c	–
7:1	0.308b	0.497b	–
8:1	0.336a	0.619a	–

[z] Means within a column and row are averaged across five agitation times (1 min – 5 min). Samples agitated by a Rotap (278 oscillations and 150 taps/min).

[y] All means reported in millimeters. Any two means within a column not followed by the same letter are significantly different at $p \leq 0.05$.

[x] Means unable to be calculated.

Table 5
Agitation time affects the standard deviation of particle size distributions.

	Particle class (width)		
Agitation time	2-mm[z]	3-mm	6-mm
1 min[y]	0.280a[x]	0.403a	--[w]
2 min	0.232b	0.356b	–
3 min	0.198c	0.322c	–
4 min	0.171d	0.311c	–
5 min	0.142e	0.306c	–

[z] Samples within each particle class are comprised of 800 particles, 100 particles from each of eight length to width ratios (1:1–8:1).

[y] A RoTap (278 oscillations and 150 taps/min) was used to agitate samples.

[x] All means reported are in millimeters. Any two means within a column not followed by the same letter are significantly different at $p \leq 0.05$.

[w] Standard deviations were unable to be calculated.

4. Conclusion

The ability of sieve analysis to sort a particle by its true sieve size is affected by the particle's L:W ratio and agitation time. It is also likely that the mass of the particle and the force applied by the agitation device influence these effects. Particles with a 1:1 ratio were measured most accurately and with the highest precision. As particles increase in size and length, a sieve's capacity to sort a material based on size diminishes. Additionally, elongated shapes (e.g., > 3:1 ratio) reduced the precision of sieve analysis to capture particles of a specific size. The significance of these results directly impacts horticultural substrate research. Granular materials with low L:W ratios, such as perlite, should be considered a candidate for accurate characterization by sieve analysis. Perlite's spherical shape would allow it to be quickly and accurately. Complex shapes and/or heterogeneous materials, such as sphagnum peat, wood fiber, and pine bark, may be difficult to accurately sort and characterize by sieve analysis. Though sieves have a long history of acceptance in the industry, alternative instruments should be evaluated for the industry to progress in the characterization of horticultural substrates. The utilization of digital image analysis has shown improvements in particle shape and size analysis compared to sieve analysis [20]. The suitability of this technique has not been evaluated for horticultural substrate components, though similar materials (biofuel feedstocks) have been studied. If, in the future, the characteristics of elongated or complex-shaped particles are desired, it may prove more beneficial to refine engineering practices than rely on sieving to precisely sort and isolate them.

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