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Particle size distribution of growing media constituents using dynamic image analysis: Parametrization and comparison to sieving

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Abstract

Growing media constituents have heterogeneous particle size and shape, and their physical properties are partly related to them. Particle size distribution is usually analyzed through sieving process, segregating the particles by their width. However, sieving techniques are best describing more granular shapes and are not as reliable for materials exhibiting large varieties of shapes, like growing media constituents. A dynamic image analysis has been conducted for a multidimensional characterization of particle size distribution of several growing media constituents (white and black peats, pine bark, coir, wood fiber, and perlite), from particles that were segregated and dispersed in water. Diameters describing individual particle width and length were analyzed, then compared to particle size distribution obtained by dry and wet sieving methods. This work suggests the relevance of two parameters, $\text{Feret}_{\text{MAX}}$ and $\text{Chord}_{\text{MIN}}$ diameters for assessing particle length and width, respectively. They largely varied among the growing media constituents, confirming their non-spherical (i.e., elongated) shapes, demonstrating the advantages of using dynamic image analysis tools over traditional sieving methods. Furthermore, large differences in particle size distribution were also observed between dynamic image analysis and sieving procedures, with a finer distribution for dynamic image analysis. The discrepancies observed between methodologies were discussed (particle segregation, distribution weighing, etc.), while describing in details methodological limitations of dynamic image analysis.

1 | INTRODUCTION

Growing media manufacturers engineer the particle size of growing media constituents to provide the plant root system the most suitable physical environment in container production. Size fractions are developed by different industrial processes (1) separation by sieving and/or screening, (2) grinding, (3) cutting, and or (4) defibration or expansion of raw materials. These actions result in the manufacture of particles with predefined size ranges, and also modify the shape and surface aspects of the particles.

Particle size distribution (PSD) of growing media constituents is considered as one of the main factors describing

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Abbreviations: Br_{MAX}, bounding rectangle length; Br_{MIN}, bounding rectangle width; $\text{Chord}_{\text{MAX}}$, maximum chord diameter; $\text{Chord}_{\text{MIN}}$, minimum chord diameter; DIA, dynamic image analysis; $\text{Feret}_{\text{MAX}}$, maximum feret diameter; $\text{Feret}_{\text{MIN}}$, minimum feret diameter; MCC, minimum circumscribed circle; MIC, maximum inscribed circle; PSD, particle size distribution.

physical properties (Bartley et al., 2022; Caron et al., 2005; Handreck, 1983; Raviv et al., 2019; Verdonck & Demeyer, 2004). PSD, in part, determines particle arrangement and consequently pore size distribution affecting water and air retention and flow properties in growing media. Several studies have described relationships between PSD and various physical properties. Generally, the larger the particle size, the higher the resulting air-filled porosity and the lowerwater retention properties (Abad et al., 2005; Bunt, 1983; Caron et al., 2005; Fields et al., 2015; Handreck, 1983; Nguyen et al., 2022; Owen & Altland, 2008).

Sieving analyses are the most common methods to analyze PSD of materials used as growing media. These methods are easy and fast to implement, reliable, cost-effective, and standard procedure exists in Europe for growing media (EN 15428, AFNOR, 2007). They are widely used by manufacturers to produce growing media according to required physical properties and to control their quality. However, the accuracy of sieving procedures is limited by the number of sieves used for separation, defining the number of particle size classes. Moreover, they do not always accurately describe the particle size, because the span of most particles is not the same in a three-axis dimension, except for spherical-like particle. Sieving procedures segregate particle according to their second largest dimension, that is, their width (Bartley, 2019; Igathinathane et al., 2009; Ulusoy & Igathinathane, 2016), also called true sieve size (Allen, 2003), except for particles with very low thickness where the diagonal aperture size should be considered (Gil et al., 2014). Gil et al. (2014) and White (2003) reported on poplar and corn stover (which are elongated and curved materials), a sieving efficiency of 70% in comparison with dynamic image analysis (DIA). Bartley et al. (2019a) also concluded that the lower the width/length ratio, the less the sieving will be able to separate the particles based on their width. Therefore, the use of sieve size as an indicator of particle size can lead to misinterpretation on particles that are non-granular. Most of the raw materials used as growing media constituents are derived from decaying organic matter (Durand et al., 2021), which are characterized by a large diversity in particle size and shape (Figure 1). Except very few granular materials (perlite, sand), most of them are elongated materials (fibers, chips, etc.) like weakly decomposed *Sphagnum* peat (also called white peat), bark, wood fiber, coir, etc., and represent more than 90% of the total volume of raw materials used as growing media (Schmilewski, 2017). Therefore, the measurement of the particle length, in addition to that of their widths, seems most relevant insofar as it is the largest dimension, which is not accurately characterized by sieving (Igathinathane et al., 2009).

Sieving results are also determined by sieving time and intensity, and growing media moisture content (Bartley, 2019; Liu, 2009). The EN 15428 (AFNOR, 2007) and the ISO 2591-1 (ISO, 1988) standard methods are based on the use of dried materials. However, the drying process can lead to a decrease in particle size for materials with an ability to shrink, and moreover to particle aggregation of particles (Robertson et al., 1984) that cannot be disaggregated during the sieving process. Also, some materials are friable and may be broken down during the sieving process. That was observed for perlite but not for peat, coir, and pine bark by Bartley et al. (2022). In this case, a wet sieving process is recommended (ISO, 1988). However, there is no other mention of this phenomenon in the literature dealing with the particle size analysis of growing media constituents.

Core Ideas

- Particle length and width are independently measured using Feret $_{\text{MAX}}$ and Chord $_{\text{MIN}}$ diameters, respectively.
- Wet dispersion for dynamic image analysis allows improved particle segregation than traditional sieving procedures.
- Dynamic image analysis allows assessment of particle size distributions of materials with a wide diversity of shapes.

Methods of wet sieving have also been developed (Allen, 1997; Levesque & Dinel, 1977; Nemati et al., 2009; Robertson et al., 1984; Yoder, 1936), and revealed a higher content of fine particles than by sieving dry material (Levesque & Dinel, 1977; Nemati et al., 2009; Robertson et al., 1984). The water helps aggregate dispersion, that is, thus particle individualization (ISO, 1988), and favors the movement of particles through the sieves with the help of the fluid. Particle elongation is also a factor in particle aggregation due to their entanglement (Gil et al., 2014), leading to an underestimation of the proportion of fine particles by PSD (Gil et al., 2012). However, no study provides information on whether wet sieving disaggregates these elongated particles.

Computer-based PSD analysis methods have been developed since 1980s for various industrial and research applications, and are now widely used, like the laser diffraction method (Polakowski et al., 2021; Yang et al., 2019) for soil particles usually ranged from 0.02 µm to 2 mm (Blott et al., 2004; Keck & Muller, 2008; Polakowski et al., 2021). For larger particle ranges like growing media constituents, DIA may be more suitable. DIA consists of taking high-frequency photos of randomly oriented particles passing through a cell, then of analyzing images using imaging tools to convert morphological characteristics into quantitative data such as distances, shapes, or surfaces. DIA methods are also widely used in various fields such as sedimentology, medicine, and for pharmaceutical and food industries. However, whatever the computer-based PSD methods, few studies have been carried out on growing media constituents by these ways, except

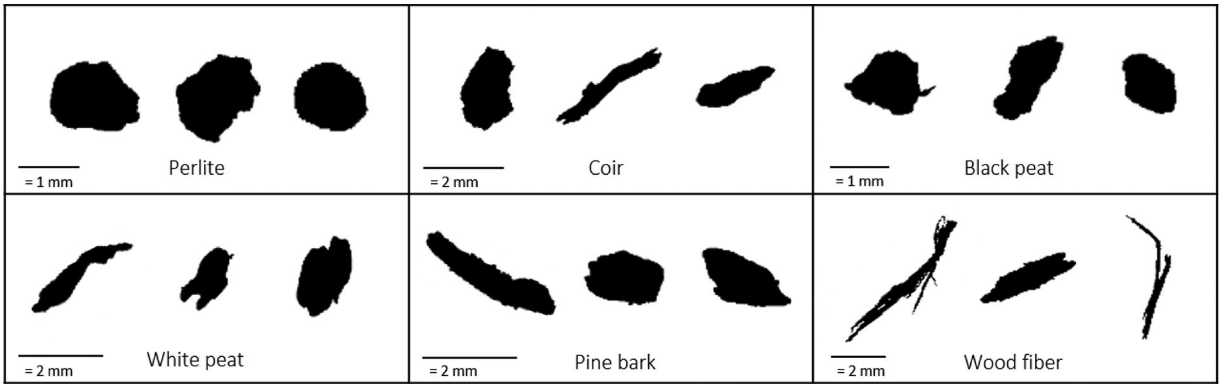

FIGURE 1 Representative images of the particle shapes provided by the QicPic device.

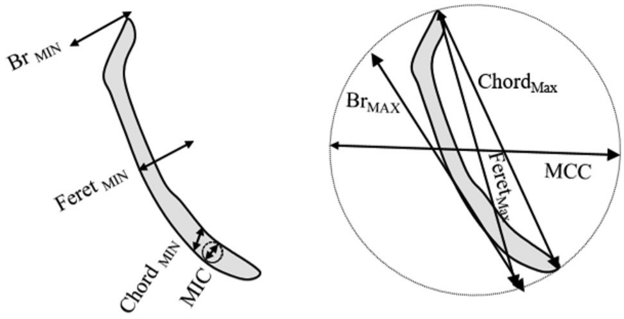

FIGURE 2 Diameters measured from Dynamic Image Analysis. Br$_{\text{MAX}}$, bounding rectangle length; Br$_{\text{MIN}}$, bounding rectangle width; Chord$_{\text{MAX}}$, maximum chord diameter; Chord$_{\text{MIN}}$, minimum chord diameter; Feret$_{\text{MAX}}$, maximum Feret diameter; Feret$_{\text{MIN}}$, minimum Feret 39 diameter; MCC, minimum circumscribed circle; MIC, maximum inscribed circle.

Bartley (2019) and Durand et al. (2021), who initiated the first description of some raw materials from DIA. Figure 1, below, highlights the particle shape diversity for the study materials.

DIA offer many diameters to describe particles morphology and then to calculate their width, length, and shape, as illustrated in Figure 2. Feret$_{\text{MAX}}$ diameter is usually considered as a good indicator for characterizing particle length, and is commonly used (Bartley et al., 2019b; Hamilton et al., 2012; Igathinathane et al., 2009; Li & Iskander, 2020; Nguyen et al., 2022; Trubetskaya et al., 2017). In contrast, some descriptors are used for assessing particle width: the Feret $_{\text{MIN}}$ (Hamilton et al., 2012; Li & Iskander, 2020), the Chord$_{\text{MIN}}$ (Nguyen et al., 2022; Trubetskaya et al., 2017), and the bounding rectangle, Br$_{\text{MIN}}$ (Bartley, 2019).

Data collected with DIA offer more detailed information about each individual particle and PSD compared to sieving methods where PSD analysis is dependent on the size and number of sieves (Igathinathane et al., 2009; Li & Iskander, 2020). Furthermore, results from sieving are expressed by unit of mass, whereas those of DIA refer to the number, size, projected surface area, or modelized volume of the particles (Li & Iskander, 2020).

The use of DIA for growing media components is to enhance the description of particle size beyond the smaller diameter of a particle. Most of the traditional work on PSD comes from the last century, are based on sieving procedures, and did not consider the large diversity of particle size and shape (fibers, chips, etc.) commonly used in growing media. These irregular sizes and shapes fall together to create a pore size arrangement and distribution much larger than in mineral soils (over 80% by volume), so that particle size and shape greatly influence the resulting matric structure of the materials, and therefore their physical and hydraulic properties (Caron & Michel, 2021; Raviv et al., 2019). A better knowledge of particle morphology is then of major importance for better predicting physical and hydraulic properties (Caron & Michel, 2021), and is then also required by substrate manufacturers to better select raw materials and/or optimize the manufacturing processes of growing media from raw materials.

The goals of this paper were:

1. To determine PSD of some main growing media components with various particle sizes and shapes by three methods (1) dry sieving, (2) wet sieving, and (3) DIA;
2. To compare PSD obtained by dry and wet sieving procedures with particle width and length distributions assessed by DIA using several size descriptors;
3. To describe benefits and limits of DIA and sieving methods, and to define diameters of interest for particle size and shape measurement derived from DIA.

2 | MATERIALS AND METHODS

2.1 | Growing media constituents

Six raw materials representing some of the main growing media constituents used worldwide (Schmilewski, 2017) were selected. They were chosen for their diversity of sizes and shapes (Bartley, 2019; Durand et al., 2021), and also by their different water and air retention properties. Information about these materials are presented in Table 1.

2.2 | Sieving procedures

2.2.1 | Dry sieving—Standardized method

Sieving dry material analysis was carried out on oven-dried materials at 40˚C to reach a moisture content lower than 15% by mass (i.e., 0.18 g of water per gram of solid), according to the EN 15428 standard method (AFNOR, 2007). However, the number of sieves with square aperture was increased for a more detailed PSD analysis, increasing from four sieves for the standard method (8-, 4-, 2-, and 1-mm aperture) to eight sieves (8-, 5-, 4-, 2-, 1-, 0.5-, 0.2-, and 0.05-mm aperture). Three repetitions per material of 125 mL each were shaken for 7 min using an AS 200 sieve shaker (Retsch), with 150 strokes/min at an amplitude of 50% (∼1.5 mm). The materials retained on each sieve were then directly weighted.

2.2.2 | Wet sieving

Wet sieving was performed with the same set of sieves, same volumes of materials, and with same duration experiment, as dry sieving method. Experiments were carried out on materials at the same moisture content they were conditioned in bags by the suppliers, without prior drying: 2.57, 4.60, 0.96, 1.94, 0.43, and 0.01 g of water per gram of solid, for white peat, coir, pine bark, black peat, wood fiber, and perlite, respectively. After the sieving process, each sieve was rinsed with water (∼1 L) on the column using a showerhead for few seconds. The materials retained on each sieve were collected in aluminum cans, placed in the oven at 105˚C for 48 h, then weighted.

2.3 | Dynamic image analysis

2.3.1 | Dynamic image analyzer "QicPic"

DIA was performed with the QicPic (Sympatec GmbH, Clausthal-Zellerfeld) using a wet dispersion unit called the Flowcell. This DIA device allowed both particle size and shape analysis from hydrated materials. This process allowed more particle dispersion prior to analysis in contrast to measuring dry materials where particle segregation was less complete. The device was equipped with a high-resolution camera, capturing images from 17 µm to 33.8 mm. Sample materials were transferred from pipes (20 mm diameter) connected to a 15 L- hydration tank containing the material to be

TABLE 1 Growing media components used and their measured physical properties.

Materials	Supplier	Origin	Extraction/process	Indicated PSD[a] (mm)	Bulk density[b] ($g\ cm^{-3}$)	Air filled porosity[b] (% volume)	Water holding capacity[b]
White peat, H5[c]	PTH	Ireland	Milled, screened	0–5	0.10	11.7	82.3
Black peat, H6–H8[c]	KD	Lithuania	Frozen, milled, sieved	0–5	0.17	10.1	78.6
Coir	PTH	Sri Lanka	Ground, sieved	0–5	0.08	22.4	72.3
Pine bark	PTH	France	Screened	0–5	0.22	42.5	43.5
Wood fiber	KD	Germany	Defibrated	2–4	0.09	63.4	31.0
Perlite	KD	Germany		0.6–2.5	0.06	56.2	39.7

Abbreviations: KD, Klasmann–Deilmann; PSD, particle size distribution; PTH, Premier Tech Horticulture France.

[a] PSD indicated by the suppliers.

[b] measured through EN 13041 procedure (AFNOR, 2000).

[c] Von Post degree of humification.

analyzed. Prior to measurement, material was agitated with a three-armed cone-shaped agitator (VJ100 Visco Jet) for 10 min to separate the particles without cutting them. The stirring process was maintained during measurement to prevent both particle flotation and sedimentation in the tank. Three replicates per material were measured, with 1–2 g of material per replicate, depending on particle size, density, and initial moisture content. This amount of material was defined to maintain an optimal optical concentration of ∼1.5%, relative to the projected area density of the particles per image. Higher densities of particles per image impeded both observe and analyze the particles individually. Each measurement event was 2 min with a frequency of 80 digital images per second, which approximately represents 10^7 particles per replicate. All particles of all images were then analyzed via the PAQXOS 4.3 software (developed by Sympatec GmbH) provided with the QicPic device. As suggested by Bartley (2019), the particle distribution was weighted by projected area, corresponding to the surface of the particle observed on the two-dimensional image. The weighting by projected area was preferred to that by volume via three-dimensional particle modeling (Li & Iskander, 2020), in order to minimize the discrepancy in the modeling of volume due to shape variability.

2.3.2 | Particle width determination

Different diameters have been measured by DIA to assess the particle width depending on their shapes, as suggested by Igathinathane et al. (2009). They allow to describe particle width in different ways, considering from the inner contour to the minimum span of the particle (Figure 2). These width diameters assessed from DIA were compared to PSD obtained by the sieving methods, also theoretically reflecting the particle segregation by their width (Gil et al., 2014; Li & Iskander, 2020; White, 2003). They are defined below and are represented in Figure 2.

- $\text{Chord}_{\text{MIN}}$: a chord length is defined by the straight distance of two points of a particle contour. Software turns the particle image by 180 degrees in steps of 9 degrees. For each rotation, the maximum horizontal chord is determined, $\text{Chord}_{\text{MIN}}$ is the shortest maximum chord among all chord measured.
- $\text{Feret}_{\text{MIN}}$: the smallest distance between two parallel tangents passing at the edge of the particle, considered as the smallest caliper distance.
- $\text{Bounding Rectangle}_{\text{MIN}}$ (Br_{MIN}): the width of the smallest rectangle that enclose the particle.
- Maximum Inscribed Circle (MIC): the diameter of the maximum inscribed circle that can be placed into the particle contour.

2.3.3 | Particle length determination

As for particle width, four diameters have been measured by DIA to assess particle length. They are defined below and represented in Figure 2.

- $\text{Chord}_{\text{MAX:}}$ the maximum chord length among all chord measured.
- $\text{Feret}_{\text{MAX:}}$ the longest distance between two parallels tangent to the particle contour, considered as the longest caliper distance.
- $\text{Bounding Rectangle}_{\text{MAX}}$ (Br_{MAX}): the length of the smallest rectangle that enclose the particle.
- Minimum Circumscribed Circle (MCC): the diameter of the minimum circle that enclose the particle.

2.4 | Methods of expression of results—Statistical analysis

PSD analyses are presented as cumulative curves for comparing DIA and sieving results. However, PSDs are weighted differently: by mass of material for sieving procedures, and by the projected area of the particles for DIA. The particle size at the 10th, 50th, and 90th percentiles of the cumulative distribution, the arithmetic means (i.e., the mean weight diameter) and their corresponding standard deviations, considered as interest values for PSD (Igathinathane et al., 2009), were determined (Table 3). The 10th and 90th percentiles, describing the size of the 10% smallest and largest particles, provide information on the span of distribution without including the extreme values, while the 50th percentile defines the median particle size. They are considered more descriptive than standard size statistics (Blott & Pye, 2001). Percentiles were determined from linear interpolations, and arithmetic means were also calculated, as suggested by Blott and Pye (2001).

Statistical analysis has been carried out with the software R studio (version 4.1.1). The following tests have been performed: Pearson's correlation matrix (package Hmisc) to study linear relationship between diameters, analysis of variance, and Tukey's honest significant difference test for mean comparison with "diameters" as qualitative variable and "mean size" as quantitative variable.

3 | RESULTS

3.1 | DIA width assessment

In general, the width diameter values ranged in ascending order as follows: $\text{MIC} \leq \text{Chord}_{\text{MIN}} \leq \text{Feret}_{\text{MIN}} = \text{Br}_{\text{MIN}}$ for all materials studied. In details, the mean comparison test (Tukey test) significantly confirmed this tendency for white and black peats, coir, and wood fiber. However, almost no

FIGURE 3 Wood fiber particles showing convex parts explaining discrepancy in various diameters assessing the width.

differences were observed between these width parameters for bark and perlite (Table 2). Bark particles were straighter and more convex, whereas perlite was more granular (attested by the lower Feret$_{MAX}$/Chord$_{MIN}$ ratio compared to the other materials), which might explain the fewer differences between width diameters measured by DIA.

Maximal differences between width diameters (calculated between MIC and Br$_{MIN}$ diameters) were close to 100 µm approximately for all materials, except for wood fiber where they reached ∼300 µm. This largest difference in width diameters for wood fiber might be due to the curvature of the long fibers and concave shapes of branched particles, largely influencing the width determination, as shown in Figures 2 and 3.

Pearson's correlation matrix of arithmetic means of size diameters highlighted that Chord$_{MIN}$ is the highest correlated diameter with the other indicators of width (Table 3). Feret$_{MIN}$ and Br$_{MIN}$ vary together ($r = 1$), as well for dry sieving and wet sieving ($r = 0.99$).

3.2 | DIA length assessment

For the same material, the mean length diameters measured were very close, and the mean comparison test (Tukey test) reported no significant differences, except for black peat (Table 2). Moreover, the Pearson correlation matrix showed that the arithmetic means of particle length diameters were correlated with each other (Table 3). Among these four particle length descriptors, Feret$_{MAX}$ always showed the highest value, whereas the other indicators were not ranged in any particular order. The mean Feret$_{MAX}$ values indicated that the particle length varied from 1.6 to 3.9 times larger than the width expressed by the Chord$_{MIN}$ diameter, for perlite and wood fiber, respectively (Table 2).

3.3 | Sieving

Considering the arithmetic mean size for all samples studied, a strong correlation was observed between dry sieving and wet sieving methods (Table 3). Wet sieving showed differences (Tukey HSD) only for white peat and coir compared to dry sieving, with a higher proportion of fine particles (Table 2). This predominance of finer particles measured from wet sieving was also observed for bark and perlite of the particle size at the 10th percentile (D10). Levesque and Dinel (1977), Robertson et al. (1984), and Nemati et al. (2009) have also reported this shift in distribution towards finer particles for wet sieving in comparison to dry sieving. This demonstrates the effect of water disaggregation of particle, allowing them to pass through a smaller sieve.

In contrast, no significant difference in particle size distribution was observed for black peat and wood fiber, whatever the sieving procedures. However, for black peat, wet sieving showed a higher proportion of finer particles in the range from 0.5 to 4 mm, in comparison to dry sieving, but no difference between the two methods is observed within the distribution of the finest particles (<0.5 mm). In view of these results, it is assumed that the disaggregation for black peat from wet sieving is less. Moreover, Feret$_{MAX}$ measured by DIA showed smaller size particles for black peat than those analyzed by sieving, and supports this hypothesis. With wood fiber, particle segregation by both sieving methods was much less accurate, seemingly due to its very elongated shape. Some particles remained entangled during dry sieving, whereas wood fiber formed mats on the sieve surface during wet sieving, considerably limiting the dispersion of particles in water.

3.4 | Particle size distribution of growing media constituents

In general, the range in PSD obtained by sieving was close to that determined by particle length (expressed from the Feret$_{MAX}$ diameter; Figure 4), and also to that given by the suppliers (Table 1).

The classification of materials based on their mean arithmetic sizes varied depending on the diameters used for characterizing particle size by DIA (Table 2), but moreover on the methods used (i.e., DIA vs. sieving).

Particle width assessed by DIA from Chord$_{MIN}$, Br$_{MIN}$, and Feret$_{MIN}$ diameters developed similar classifications (black peat < white peat < coir < pine bark < wood fiber < perlite), but MIC moved the wood fiber up in the distribution hierarchy (black peat < white peat < wood fiber < coir < pine bark < perlite) presumably due to its convex and branched shapes (Figure 3). Classification differed when considering particle length assessed by DIA from Feret $_{Max}$ diameter (black peat < white peat < coir < pine bark < perlite < wood fiber).

A same classification according to arithmetic mean particle size was described for both sieving methods (white

TABLE 2 10th, 50th, and 90th percentiles, arithmetic mean sizes, and associated standard deviations (in brackets), calculated from sieving procedures and DIA.

Raw materials	Size method determination (µm)	Size at the 10th percentile (D_{10}) (µm)	Size at the 50th percentile (D_{50}) (µm)	Size at the 90th percentile (D_{90}) (µm)	Arithmetic mean size (µm)			
Irish white peat	MIC	49 (0.8)	221 (9.7)	646 (29.9)	294 (10.4)	c[a]		
	$\text{Chord}_{\text{MIN}}$	60 (2.5)	253 (10.5)	748 (36.6)	347 (12)	B		D[c]
	Br_{MIN}	70 (2.7)	296 (11.1)	854 (41.8)	397 (14.7)	A		
	$\text{Feret}_{\text{MIN}}$	70 (2.5)	294 (11.1)	844 (41.9)	393 (14.6)	A		
	MCC	117 (7.1)	624 (32.0)	1684 (45.0)	808 (29.9)		a[b]	
	$\text{Chord}_{\text{MAX}}$	105 (7.1)	614 (31.9)	1652 (48.8)	794 (29.8)		a	
	Br_{MAX}	101 (6.0)	606 (32.1)	1636 (48.8)	787 (30.6)		a	
	$\text{Feret}_{\text{MAX}}$	108 (6.6)	627 (33.4)	1696 (78.6)	812 (32.6)		a	B
	Wet sieving	106 (4.6)	567 (17.8)	1317 (19.2)	740 (11.5)			C
	Dry sieving	194 (6.3)	648 (4.8)	1796 (62.3)	939 (23)			A
Coir	MIC	55 (3.6)	238 (22.2)	846 (32.6)	362 (15.6)	c		
	$\text{Chord}_{\text{MIN}}$	75 (7.7)	267 (27.2)	936 (32.0)	411 (15)	b		C
	Br_{MIN}	86 (10.7)	296 (28.8)	1048 (33.7)	468 (15.3)	a		
	$\text{Feret}_{\text{MIN}}$	84 (9.3)	293 (28)	1035 (35.5)	462 (15.1)	a		
	MCC	126 (11.3)	438 (43.7)	1787 (78.1)	808 (43.3)		a	
	$\text{Chord}_{\text{MAX}}$	116 (11.3)	432 (42.3)	1826 (74.3)	839 (83.3)		a	
	Br_{MAX}	110 (9.6)	417 (41.0)	1783 (72.6)	823 (85.1)		a	
	$\text{Feret}_{\text{MAX}}$	123 (13.8)	443 (43.6)	1850 (71.8)	857 (84.6)		a	AB
	Wet sieving	104 (3.3)	539 (16.8)	1585 (8.7)	771 (3.6)			B
	Dry sieving	265 (4.5)	669 (14.4)	1806 (53.5)	974 (22)			A
Fresh pine bark	MIC	47 (9.3)	219 (24.1)	990 (87.6)	418 (43.3)	a		
	$\text{Chord}_{\text{MIN}}$	55 (9)	248 (28.5)	1123 (95.8)	470 (46.9)	a		C
	Br_{MIN}	64 (7.4)	272 (29.3)	1215 (96.9)	515 (50)	a		
	$\text{Feret}_{\text{MIN}}$	64 (7.2)	270 (28.8)	1207 (95.5)	510 (49.5)	a		
	MCC	102 (11.1)	436 (53.7)	2459 (161.6)	964 (80.8)		a	
	$\text{Chord}_{\text{MAX}}$	87 (12.5)	436 (54.9)	2528 (169.3)	986 (87.4)		a	
	Br_{MAX}	79 (12.4)	424 (55.6)	2497 (173.4)	971 (87.5)		a	
	$\text{Feret}_{\text{MAX}}$	88 (11.4)	446 (56.5)	2557 (177.5)	1003 (89.1)		a	B
	Wet sieving	222 (12.4)	1159 (46.1)	3628 (86.8)	1628 (54.8)			A
	Dry sieving	364 (82)	1361 (160.4)	3779 (264.1)	1859 (193)			A
Black peat	MIC	17 (0.1)	110 (1.2)	423 (7.6)	194 (3.7)	c		
	$\text{Chord}_{\text{MIN}}$	31 (0.0)	131 (1.7)	498 (10.8)	230 (7.1)	b		C
	Br_{MIN}	34 (0.1)	160 (1.6)	565 (12.6)	264 (6.2)	a		

(Continues)

TABLE 2 (Continued)

Raw materials	Size method determination (µm)	Size at the 10th percentile (D_{10}) (µm)	Size at the 50th percentile (D_{50}) (µm)	Size at the 90th percentile (D_{90}) (µm)	Arithmetic mean size (µm)			
	$Feret_{MIN}$	34 (0.1)	158 (1.6)	560 (12.8)	261 (6.2)	a		
	MCC	70 (0.3)	268 (3.2)	1107 (18.7)	487 (7.9)		a	
	$Chord_{MAX}$	56 (0.4)	256 (3.4)	1102 (16.8)	476 (8.7)		ab	
	Br_{MAX}	53 (0.3)	243 (3.0)	1091 (15.9)	466 (5.6)		b	
	$Feret_{MAX}$	63 (0.2)	268 (3.3)	1124 (15.9)	490 (8.2)		a	B
	Wet sieving	105 (6.4)	501 (23.5)	2679 (188.3)	1003 (53)			A
	Dry sieving	101 (11.2)	558 (105.3)	3009 (281.9)	1111 (131)			A
Wood fiber	MIC	17 (0.3)	106 (14.1)	941 (103.4)	313 (52.6)	c		
	$Chord_{MIN}$	31 (0.4)	150 (26.4)	1418 (211.8)	475 (69.8)	b		B
	Br_{MIN}	35 (0.5)	255 (35.9)	1770 (212.8)	631 (77.3)	a		
	$Feret_{MIN}$	35 (0.5)	255 (36)	1759 (214.1)	627 (77)	a		
	MCC	73 (0.5)	830 (97.3)	4462 (756.4)	1692 (195.5)		a	
	$Chord_{MAX}$	61 (1.5)	863 (115.0)	4952 (916.0)	1791 (231.9)		a	
	Br_{MAX}	58 (1.4)	879 (117.3)	5006 (919.9)	1822 (239.5)		a	
	$Feret_{MAX}$	68 (1.1)	895 (121.3)	5117 (972.7)	1859 (249)		a	A
	Wet sieving	157 (8)	1398 (42.5)	3936 (190.8)	1866 (64)			A
	Dry sieving	154 (20.2)	1615 (80.6)	4174 (68.1)	2067 (101.2)			A
Perlite	MIC	15 (0.3)	313 (1.8)	1515 (44.7)	573 (20.9)	a		
	$Chord_{MIN}$	17.1 (0.5)	357 (1.7)	1627 (83.8)	632 (28.4)	a		B
	Br_{MIN}	28 (0.7)	384 (2)	1721 (86.4)	671 (28.7)	a		
	$Feret_{MIN}$	28 (0.7)	379 (1.7)	1702 (82.3)	664 (28.5)	a		
	MCC	63 (1.4)	484 (0.4)	2500 (16.5)	966 (20.9)		a	
	$Chord_{MAX}$	35 (3.6)	528 (8.1)	2517 (5.1)	984 (20.5)		a	
	Br_{MAX}	33 (0.6)	506 (8.1)	2465 (8.1)	956 (17.8)		a	
	$Feret_{MAX}$	49.2 (2.1)	537 (7.5)	2538 (2.3)	998 (20.3)		a	A
	Wet sieving	22 (2.7)	928 (47.6)	1784 (17.2)	975 (13.5)			A
	Dry sieving	30 (4.8)	1076 (37.4)	1857 (23.1)	1075 (19.3)			A

Abberviations: Br_{MAX}, bounding rectangle length; Br_{MIN}, bounding rectangle width; $Chord_{MAX}$, maximum chord diameter; $Chord_{MIN}$, minimum chord diameter; DIA, dynamic image analysis; $Feret_{MAX}$, maximum Feret diameter; $Feret_{MIN}$, minimum Feret 39 diameter; MCC, minimum circumscribed circle; MIC, maximum inscribed circle.

[a] Letters in this column indicate statistically significant differences between the means of the width diameters measured by DIA.

[b] Letters in this column indicate statistically significant differences between the means of the length diameters measured by DIA.

[c] Upper case letters indicate statistically significant differences between the means Chord $_{MIN}$ and Feret $_{MAX}$ (measured by DIA) and mean particle size obtained by sieving methods for each material.

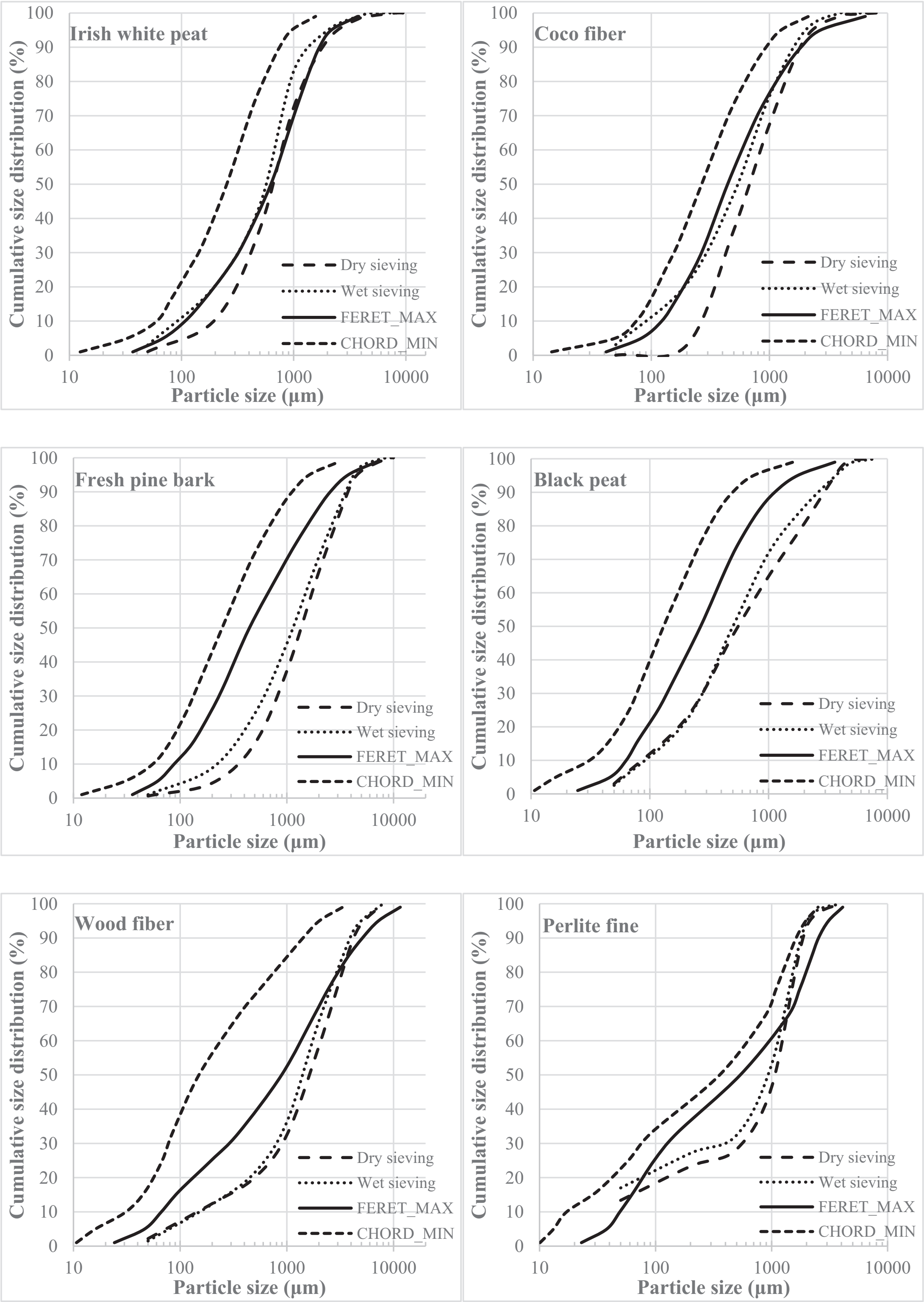

FIGURE 4 Cumulative particle size distribution of white peat, coir, pine bark, black peat, wood fiber, and perlite measured through dry and wet sieving and dynamic image analysis (where $\text{Feret}_{\text{MAX}}$ and $\text{Chord}_{\text{MIN}}$ were chosen as representative particle length and width descriptors, respectively). $\text{Chord}_{\text{MIN}}$, minimum chord diameter; $\text{Feret}_{\text{MAX}}$, maximum Feret diameter.

TABLE 3 Pearson's correlation matrix of arithmetic mean of size estimators.

	DIA parameters									
	Br_{MIN}	$Chord_{MIN}$	$Feret_{MIN}$	MIC	Br_{MAX}	$Chord_{MAX}$	$Feret_{MAX}$	MCC	Wet sieving	Dry sieving
Br_{MIN}	1									
$Chord_{MIN}$	0.95*	1								
$Feret_{MIN}$	1*	0.95*	1							
MIC	0.79	0.94*	0.79	1						
Br_{MAX}	0.73	0.50	0.74	0.18	1					
$Chord_{MAX}$	0.75	0.52	0.76	0.21	1*	1				
$Feret_{MAX}$	0.74	0.51	0.75	0.19	1*	1*	1			
MCC	0.76	0.53	0.76	0.21	1*	1*	1*	1		
Wet sieving	0.46	0.27	0.46	0.02	0.76	0.76	0.76	0.76	1	
Dry sieving	0.44	0.26	0.45	0.01	0.77	0.77	0.77	0.77	0.99*	1

Abbreviations: Br_{MAX}, bounding rectangle length; Br_{MIN}, bounding rectangle width; $Chord_{MAX}$, maximum chord diameter; $Chord_{MIN}$, minimum chord diameter; $Feret_{MAX}$, maximum Feret diameter; $Feret_{MIN}$, minimum Feret 39 diameter; DIA, dynamic image analysis, MCC, minimum circumscribed circle; MIC, maximum inscribed circle.

*Significant (p-value < 0.01).

peat < coir < perlite < black peat < pine bark < wood fiber). However, classifications from DIA and sieving procedures largely differed.

4 | DISCUSSION

4.1 | Prior comment about sieving procedures

The number of sieves used in this study was twice that of EN 15428 standard procedure (AFNOR, 2007), and thus gave a more detailed PSD and robust statistical analysis, as also reported by Blott and Pye (2001). The high proportion of particles smaller than 1 mm demonstrated the use of complementary sieves (50, 200, and 500 µm) in our study. Note that in the case of perlite, <50 µm particles represented ∼15% by mass, and then did not allow to accurately assess the particle size at the 10th percentile of the cumulative size distribution.

4.2 | Diameters of interest and choice of relevant diameters from DIA

There are various ways to describe particle width (White, 2003); each diameter providing relevant information. However, $Feret_{MIN}$ and Br_{MIN} diameters are influenced by the curvature of the particles, and MIC minimizes the value of the width for particles presenting concave and/or convex shapes. Considering the irregular shapes of raw materials used as growing media components, and the presence of more or less curved shapes of the elongated particle (fibers), the $Chord_{MIN}$ was chosen as the reference diameter for particle width. This diameter is strongly correlated with the other descriptors, $Feret_{MIN}$ and Br_{MIN} on the one hand and MIC on the other, although these parameters are not related to each other. Thus, in view of this relation, it seems to be a good choice. It may also be considered as the most suitable descriptor of particle width, when characterized using sieving and DIA (Trubetskaya et al., 2017). This diameter was also previously used by Nguyen et al. (2022) to describe particle width of growing media components.

In contrast with the particle width assessment, all particle length diameters measured on the same material were very similar, whatever the curvature and the concave or convex shapes of particles (as described in Figure 2). Hence, $Feret_{MAX}$ has been chosen as an indicator of particle length, because this diameter is usually used as a reference to describe particle length (Igathinathane et al., 2009) and previously served for growing media components (Bartley, 2019; Nguyen et al., 2022).

TABLE 4 Main characteristics and discrepancies of methods used.

Sieving	QicPic
PSD by unit of mass	PSD by projected area, modeled volume, size, or number of particles; here projected area
Volume of materials per replicate: 125 mL[a] (i.e., 10–20 g)	Mass of materials per replicate: 2–3 g (several hundreds of thousands of particles)
Material preparation: oven dried materials at 40˚C (dry sieving)[a], or hydrated materials (wet sieving)	Material preparation: dry or wet materials, depending on the QicPic particle dispersion system used; here preliminary dispersion in water by stirring
Particle separation: shaking of the sieve set	Particle separation: depending on the QicPic particle dispersion system used; here wet dispersion unit (Flowcell)
Experiment duration: 7 min shaking[a]	Experiment duration: 2 min maximum (+10 min preliminary dispersion in water)
Range of measurement: 50 µm–30 mm, depending on the sieve set (minimum 4 sieves[a]); here eight sieves used	Range of measurement: depending of the lens used; here 17 µm–34 mm for lens M9, but limited to 20 mm in width
Particle size fractions generated Single dimensional particle characterization Discrete values	Particle individualization Multidimensional particle characterization Continuous values
Accuracy of PSD depending on: - the number and size apertures of sieves used, - the particle shape	Accuracy of the PSD depending on the orientation of the particles in front of the camera Particle size measurement accuracy <0.1 µm
Low-cost tool	Expensive cost tool
DM: standardized method (EN 15428, AFNOR , 2007 for growing media)	No standard
Many scientific references based on this method	Few scientific references

[a] EN 15428 standard method.

4.3 | Interest of DIA and limits

4.3.1 | Multidimensional characterization

Describing growing media components from sieving is simple, but simplistic, because these materials largely differ by their width, length, and shapes, which influence the sieving results (Bartley, 2019; Ulusoy & Igathinatane, 2016). The use of DIA is then relevant to assess the particle width, length, and shape, and thus to allow a better description of particle morphology. That represents an important step forward and will help in the analysis and understanding of resulting particle arrangement and physical properties. The present study was conducted on only six materials, chosen both for their representativeness as main growing media constituents and their diversity in terms of physical properties (Table 1) and particle size (Table 2). However, this low number of samples could not allow to accurately draw conclusions linking particle morphology and physical properties. However, from a large diversity of growing media constituents, Durand et al. (2022) have already fitted polynomial regressions describing strong relationships between increasing water holding capacity and decreasing mean particle width, and even more mean particle length (considering $\mathrm{Chord}_{\mathrm{MIN}}$ and $\mathrm{Feret}_{\mathrm{MAX}}$, respectively); whereas correlation was conversely very low between water holding capacity and mean particle size determined from dry sieving. That proves the relevance of measuring particle length and width by DIA, to which analysis of solid phase and pore space organization should also be developed, in order to better predict physical properties.

4.3.2 | Weighing according to the projected area

Traditional soil science has an inherent bias toward mass-type measurements. In horticultural substrates, volumetric measures are much more common and descriptive, as components and substrates are much lighter and much less dense. DIA measurements are more descriptive for shape and size analysis than sieving for substrates, in part, because of the multidimensional and therefore more volumetric nature of their data.

However, our works suggested to express PSD from DIA in reference to the projected area of particles. However, Li and Iskander (2020) reported that the projected area-weighted distribution gives more importance to smaller particles than to larger ones, in contrast to PSD by mass (sieving) or volume. Weighting by volume is possible with some DIA tools (including the QicPic) and would be preferable, but is unfortunately based on a single and predefined shape model (sphere, ellipse, or cylinder). It is then not suitable for growing media components, due to their large diversity of shapes (Bartley, 2019; Durand et al., 2021), because it would induce a poor estimation of the real weight of the particles in the distribution.

4.3.3 | Other methodological limits of QicPic

The measurement range for the QicPic device extends from 17 to 20 mm in particle width, corresponding to the minimal resolution of the camera lens used and to the aperture size of the wet dispersion unit of the QicPic, respectively. This measurement range is then suitable for most of the growing media components. Although analyzing growing media PSD from DIA on wet materials is more relevant, the use of the QicPic can be problematic for materials like perlite. The low densities coupled with trapped air created in particle expansion of perlite create buoyant particles on the water surface of the tank, that have to be manually inserted in the pipe driving the particles to the wet dispersion unit.

The orientation of particles for DIA analysis as they pass randomly in front of the camera can also substantially influence the assessment of particle length and width (Hamilton et al., 2012; Trubeskaya et al., 2017) that can lead to an underestimation of particle length. It also underestimates particle width for particles presenting a thickness much smaller than its width in case of the particle thickness is exhibited in front of the camera (e.g., bark particles). Conversely, an overestimation of particle width is also possible if the width and thickness are both exhibited in front of the camera.

4.4 | Discrepancies between methods

4.4.1 | DIA and sieving

Except $\mathrm{Feret}_{\mathrm{MAX}}$ which refers to the particle length, the particle size distributions and resulting classifications of materials according to their mean particle size obtained by DIA ($\mathrm{Chord}_{\mathrm{MIN}}$, $\mathrm{Br}_{\mathrm{MIN}}$, $\mathrm{Feret}_{\mathrm{MIN}}$, and MIC) and sieving procedures differed although they theoretically consider the width of the particles.

The principle of particle segregation and the quantities used between methods are two of the criteria that may influence these differences. Only 2–3 g of materials are used and previously stirred in water for 10 min, allowing an efficient particle segregation before DIA analysis of each particle. In contrast, a much larger quantity of materials (125 ml, i.e., 10–20 g approximately depending on the materials) is directly shaken for 7 min and segregated through a column of eight sieves. However, particle separation during sieving procedures, with or without water, appeared to be incomplete, especially for black peat particles where the cohesion of aggregates is strong, and inaccurate for elongated materials such as wood fiber particles due to their shapes, as already reported by Bartley (2019) and Gil et al. (2014), but also because a tangle of fibers is often observed, limiting particle separation.

Also, sieving results are plotted within nine classes (corresponding to the use of 8 sieves) according to cumulative undersize mass distribution, for which the proportion is affected by the upper sieve size aperture. Particle size is then overestimated within a class, in contrast with DIA where all particle sizes are considered. Consequently, sieving results in a coarser, and less descriptive PSD in comparison with DIA.

Moreover, particle size distributions obtained from sieving and by DIA are not expressed by the same unit of reference: by unit of mass for sieving, and by projected surface area for DIA. But, weighting the distribution by projected area for DIA (vs by mass for sieving) increases the weight of small particles in the distribution, as demonstrated by Bartley (2019).

Table 4 summarizes some of the main characteristics of both DIA (coming from the QicPic tool) and sieving methods.

4.4.2 | Sieving methods

Although results from both sieving methods are highly correlated, PSD obtained from wet sieving systematically showed smaller particles than those from dry sieving, especially since shrinkage was observed for some materials after drying (in particular, peats). The differences in the arithmetic mean size are in the order of hundreds of microns, representing a gap varying from 5% to 20% for perlite and white peat, respectively, that confirmed the better individualization of particles due to the disaggregation, already reported by Nemati et al. (2009). However, particle segregation seemed to be still incomplete when comparing these values to the particle size measured from DIA.

5 | CONCLUSION

DIA provides a multidimensional description of PSD according to particle morphology of growing media constituents, which is highly relevant due to their diversity in shapes. The use of $\mathrm{Chord}_{\mathrm{MIN}}$ and $\mathrm{Feret}_{\mathrm{MAX}}$ are direct measurements of individual particles that have been suggested to assess particle width and length, respectively. Although DIA tools are expensive, they are quite easy and fast to use, and the QicPic device with a wet dispersing unit allows the better particle segregation and provides a more descriptive and detailed PSD analysis than sieving methods. These measurements directly describe particle morphology in ways never before reported. That should lead to describing particle arrangement, and resulting physical properties.

AUTHOR CONTRIBUTIONS

Stan Durand: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; visualization; writing—original draft; writing—review and editing. **Brian Jackson**: Writing—review and editing. **William Fonteno**: Project administration; supervision; validation; writing—review and editing. **Jean-Charles Michel**: Conceptualization; funding acquisition; project administration; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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