New tools for particle shape analysis of substrate components: initial results and future prospects

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Abstract

Substrate components are classified and selected for mixes in part based on their particle size determined through sieving processes. However, sieving tools and methods do not directly consider particle shape. The irregular shapes and sizes of substrates components create a large pore volume (over 85%), of which the shape and size of particles greatly influence the resulting matric structure of the materials, and therefore their physical properties (water retention, drainage). Particle shape of coco fiber, pine bark, wood fiber and white peat were studied with two dynamic image analyzers: the QicPic and the CPA2, based on wet and dry dispersion, respectively. Distribution of shape descriptors (elongation, circularity and roundness of materials) were calculated and analyzed, in relation to the particle size. Results showed that the materials tested are highly elongated and very angular, with a low circularity. Circularity decreased and elongation increased with an increase in particle size, while roundness remained very low. Despite the different methods of sample preparation and calculation models, both QicPic and CPA2 tools were able to image and quantify similar particle shapes in these substrates effectively.

Keywords: QicPic, computerized particle analyzer, dynamic image analysis

INTRODUCTION

Substrate manufacturers engineer the particle size of growing media constituents to provide the plant root system the most suitable physical environment. Particle size distribution (PSD) of growing media constituents is one of the main factors explaining physical properties. PSD will in part determine particle arrangement and consequently water and air retention and flow properties of substrates. Several researchers have described relationships between PSD and various physical properties. Generally, the larger the particle size, the higher the air-filled porosity (AFP), and the lower the water retention properties (Bunt, 1983; Handreck, 1983; Abad et al., 2005; Caron et al., 2005; Fields et al., 2015). Conversely, the smaller the particle size, the smaller the mean radius of pores (Owen and Altland, 2008), and the higher the bulk density of the substrate (Rezanezhad et al., 2010).

Sieve analysis is relevant for granular particles. However, most horticultural substrate components are organic and show a large diversity of irregular shapes with fibers, chips, and plates, which are far from spherical. Bartley (2019) demonstrated that the more a particle elongates, the smaller is the accuracy of the PSD. This large diversity of particle shapes of raw materials also is constantly changing through decomposition. Clearly, particle shape must be considered when trying to engineer new substrates for the future.

Significant improvement in dynamic image analysis in the past years has improved particle shape analysis, like recent works developed on dry materials by Bartley (2019) using the Computerized Particle Analyzer (CPA2, W.S. Tyler Group, USA), allowing analysis of shape and size of particles up to 45 mm.

Another device that measures particle shape is the QicPic (Sympatec GmbH, Germany). The major difference from CPA2 is it analyzes particle shape of materials dispersed through water rather than dry through to CPA2. This device can detect particles shape from 50 µm to 34 mm. Both methods provide shape information using different technologies and sample preparations (wet and dry dispersion). The objectives of this study were to derive particle

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shapes of four substrate components, using both CPA2 and QicPic methods, and to highlight the similarities and differences between both methodologies.

MATERIALS AND METHODS

Samples

Experiments were carried out on four commercialized growing medium constituents (Figure 1): a 0-25 mm coco fiber (medium) from Ivory Coast provided by Premier Tech; a screened 5-10 mm fresh pine bark (*Pinus maritima*) from France, provided by Premier Tech Horticulture; a 0-4 mm medium wood fiber (*Picea* and/or *Abies*) provided by Klasmann-Deilmann and a star screened 5-20 mm, Latvian white milled peat (H2-H5 Von Post index) provided by Floragard.

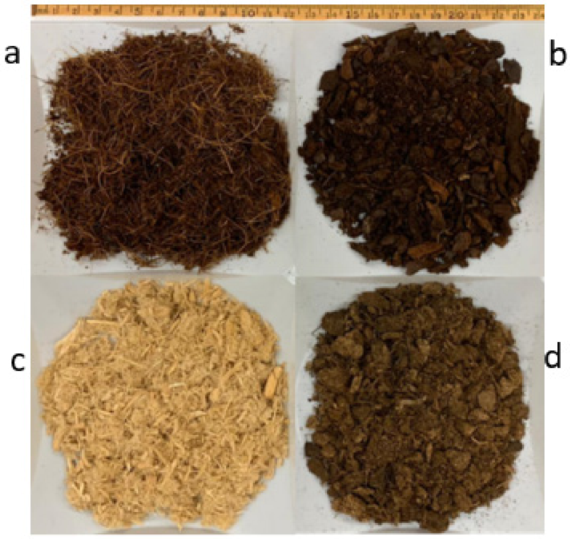

Figure 1. Study materials: a) coco fiber, b) pine bark, c) wood fiber, d) white milled peat.

Tools for particle shape acquisition

The methodologies for determining particle shape are very different from particle size. In both techniques, particle shapes are determined by passing individual particles across a high-speed camera to obtain digital images of each particle. Because most substrate particles are light, this results in at least 1,000 particle images from a single gram of sample.

Also, the general sample preparation used for these two techniques are quite different, as one used wet materials and the other uses a dry format. The particle shapes are collected and cataloged for further analysis. Along with shape a form of particle size distribution can also achieved. Although no sieves are used, the various particles can be collected into specific ranges similar to sieve analysis and the number and volume of particles can be displayed.

1. QicPic – wet preparation.

Approximately 2-3 g of material at 66% mass moisture (representing tens of thousands of particles) content were stirred with ~10-15 L water in a tank for 15 min, then passed through the QicPic with a constant flow controlled by a peristaltic pump, and circulated through a flow cell equipped with a camera for continuous image recording. Three repetitions were carried out (over a 10 min period, each). Particle shapes were then analyzed with the associated software, PAQXOS. The device is able to detect particle shapes in a range from 50 µm to 33.8 mm.

2. CPA2 – dry preparation.

Approximately 8-10 mL (i.e. 5 to 10 thousand of particles) of air-dried materials (i.e., below 14% moisture content) was positioned on a vibrating feeder of the machine, then particles were carried by conveyor belt to fall in front of a high-speed resolution camera. Three repetitions were carried out (15 min each). Particle shapes were analyzed by the associated software, allowing their accurate determination in the range varying from 500 µm to 45 mm. Below 500 µm, too many visual artifacts developed. Therefore, particles <500 µm were removed by sieving prior to imaging.

Particle shape analysis

To quantify the weighted value of each particle for shape distribution analysis, its volume is modeled from the equivalent diameter, d_{EQPC}, of the circle (EQuivalent Projection area Circle, EQPC) having the same projected area (Figure 2a).

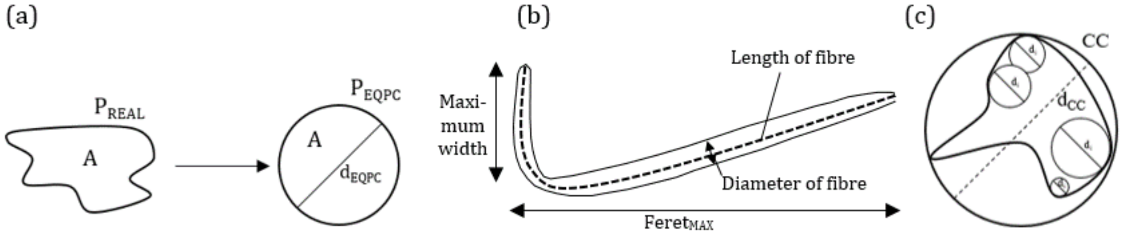

Figure 2. Diameters used for particle shape calculation and volume model: (a) equivalent perimeter, P_{EQPC}, for circularity calculation, and equivalent diameter, d_{EQPC}, for sphere modeling, (b) diameter and length of fiber, maximum width and $Feret_{MAX}$ for elongation calculation, (c) diameter of the circumscribed circle and diameters of the curvatures of convex regions for roundness calculation.

1. Diameters definition.

In this work, an estimation of particle size is developed from each image by using the $Feret_{MAX}$ diameter, corresponding to the maximal distance between two parallel tangents of the particle contour (Figure 2b). The maximum width is the largest extend orthogonal to the $Feret_{MAX}$ (Figure 2b). The length of the skeletonized particle (length of fiber) is the distance between the farthest extremities of a particle within its contour and the diameter of fiber, obtained by dividing the projected area by the sum of all length of the branches of the fiber skeleton (Figure 2b). The circumscribed circle is the circle enclosing the particle contour (Figure 2c).

2. Shape descriptors definition.

Ratios of diameter and projection area are then used for the calculation of three common shape descriptors (Blott and Pye, 2008): elongation, circularity and roundness.

The elongation corresponds to the ratio of the width to the length of a particle. The smaller its value, the greater is the elongation. Neither tool use the same diameters to calculate the particles elongation: the total length of a curved particle and the diameter of fiber are considered for the QicPic (Equation 1a), in contrast with the CPA2 where the diameter $Feret_{MAX}$ and the maximum width of fiber are used (Equation 1b). Consequently, values for elongation will be underestimated for the CPA2 in comparison with those from the QicPic.

$$Elongation_{QicPic} = \frac{diameter\ of\ fibre}{lenght\ of\ fibre} \tag{1a}$$

$$Elongation_{CPA2} = \frac{maximum\ width}{Feret_{MAX}} \tag{1b}$$

The circularity is the ratio of the EQPC perimeter to the real perimeter of the particle according to Wadell (1933) (Equation 2). That shape descriptor does not refer to the circular shape like of a particle or the angularity of its edges. Indeed, a square is considered to have a moderate circularity (=0,89). The circularity refers to the regularity of the particle contour, its deformation from a perfect circle, which is the shape having the smallest perimeter for a given area.

$$Circularity = \frac{2\sqrt{\pi A}}{P} \tag{2}$$

where A is the area of the particle and P the perimeter of the particle.

The roundness refers to the relative sharpness of corner and edges of a particle. For the QicPic, this shape descriptor was calculated from the ratio of the averaged radius of curvature of all convex regions to the circumscribed circle of the particle (Equation 3a). For the CPA2, roundness consists in measuring the degree of similarity of the particle projection area of the particle to the projection area of a circle having the same projection area (Equation 3b).

$$Roundness_{QicPic} = \frac{\sum \frac{d_i}{D}}{n} \tag{3a}$$

where d_i is the diameter of the curvature of the convex region, D is the diameter of the circumscribed circle and n is the number of convex region (Figure 2c).

$$Roundness_{CPA2} = \frac{4A}{\pi Feret_{MAX}{}^2} \tag{3b}$$

The class designation for shape descriptors were defined from the referential proposed by Blott and Pye (2008). However, due to the use of other calculation models, the class limits were changed for circularity and roundness in order to fit the same geometrical dimensions.

RESULTS

Particle size distribution

The different measuring ranges between both QicPic (50 µm-33,8 mm) and CPA2 (500 µm-45 mm) resulted in a shift toward larger size distribution for the CPA2, in comparison with the QicPic. 52, 16, 11 and 8% in mass (representing <0,5 mm particles) for coco fiber, wood fiber, pine bark, and white peat, respectively, were indeed removed by sieving prior to CPA2 measurements. Combining results from both devices indicated that coco fiber presented the widest PSD (with significant parts of smaller and larger particles than the other materials), whereas peat, wood fiber and pine bark showed a narrower PSD (Figure 3).

Particle shape distribution

A visual representation of the different particle elongation, circularity and roundness classes, with their proportion of each material, is presented on Figure 4.

QicPiC described materials to be extremely and very elongated, with 73, 86, 92 and 95% in mass proportion for coco fiber, pine bark, peat and wood fiber, respectively. Particles elongation was much lower from the CPA2 for pine bark, peat and wood fiber, where moderate to not elongated particles represented 85, 79, 39% in mass, respectively. The decrease in elongation between QicPic and CPA2 was also show in a lesser degree for coco fiber, with a decrease in extremely elongated particles (52 vs. 21%) for the benefit of very elongated particles (38 vs. 37%).

The discrepancy observed for elongation between QicPic and CPA2 can be mainly explained by the different parameters used for its calculation (described in the section Methods of particle size and shape analysis), so that the QicPic gives higher degree of elongation than measured by the CPA2. This is also supported by the relationship between particle size and shape (Figure 5), showing that smaller particles (removed for CPA2 measurements) were also the lesser elongated.

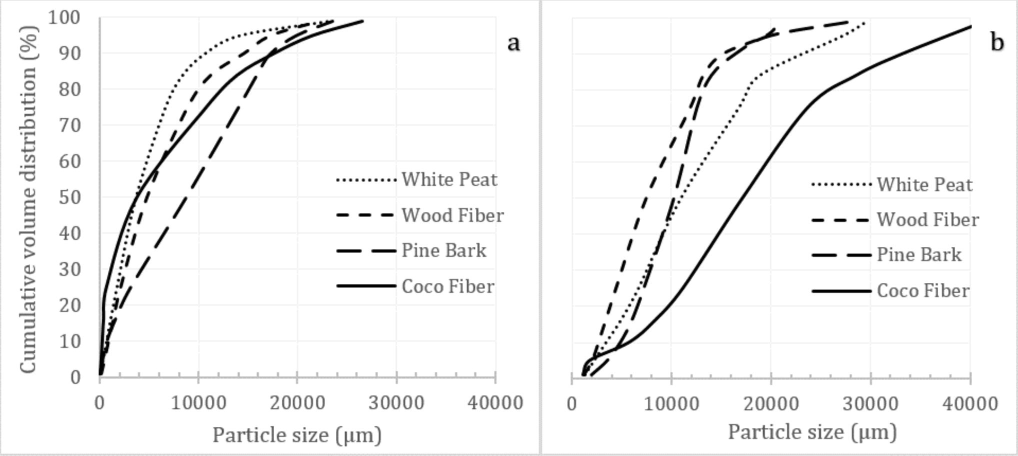

Figure 3. Cumulative size distribution by volume obtained by (a) QicPic, (b) CPA2.

The distribution of circularity was quite close for both QicPic and CPA2, indicating that all materials presented a low to very low circularity. The sum of these two classes represented from 79-97% of particles in mass proportion with QicPic, and from 79-99% with CPA2.

Conversely, large differences between QicPic and CPA2 were observed about roundness, mainly due to the very different calculation models used for its estimation. For QicPic, most of them are very angular, representing 60% for coco fiber, 66% for pine bark and peat, and up to 85% for wood fiber. Using CPA2, only coco fiber was mainly represented by very angular particles. Wood fiber showed particles with large diversity of roundness, from very angular to rounded particles, whereas pine bark and white peat were mainly represented by sub-rounded and rounded particles with the CPA.

From the QicPic, a relationship between elongation, circularity and roundness was observed, indicating the more the particles are elongated, the less their circularity, the more angular the particles. This relationship was not shown with the CPA2. This could be explained by the different calculation models used for elongation and roundness with CPA2, leading to underestimate the elongation, and to overestimate the roundness of particles, in comparison with the QicPic.

Evolution of the shape descriptors as a function of size

Considering all materials, evolution of shape as a function of the size showed a quite similar tendency. The larger the particle size (i.e. the Feret$_{MAX}$), the lower the circularity and the roundness, the greater the elongation. Thus, smaller particles were less elongated, more circular, and less angular than coarser particles which were very elongated, angular, and not circular.

From the QicPic, all materials showed a decrease from high/moderate circularity to a low circularity, an increase of elongation from moderately to extremely elongated after ~1 mm, and a decrease in roundness from angular to very angular particles. From the CPA2, smaller changes in the values of all shape descriptors were observed due to (1) the removal of <0,5 mm particles, (2) the calculation models used by the CPA2 for elongation and roundness. Parameters used for calculating elongation limit the probability of having extremely elongated particles, whereas the classification (Blott and Pye, 2008) used for the roundness was irrelevant for the CPA2 data, due to the parameters measured for its calculation.

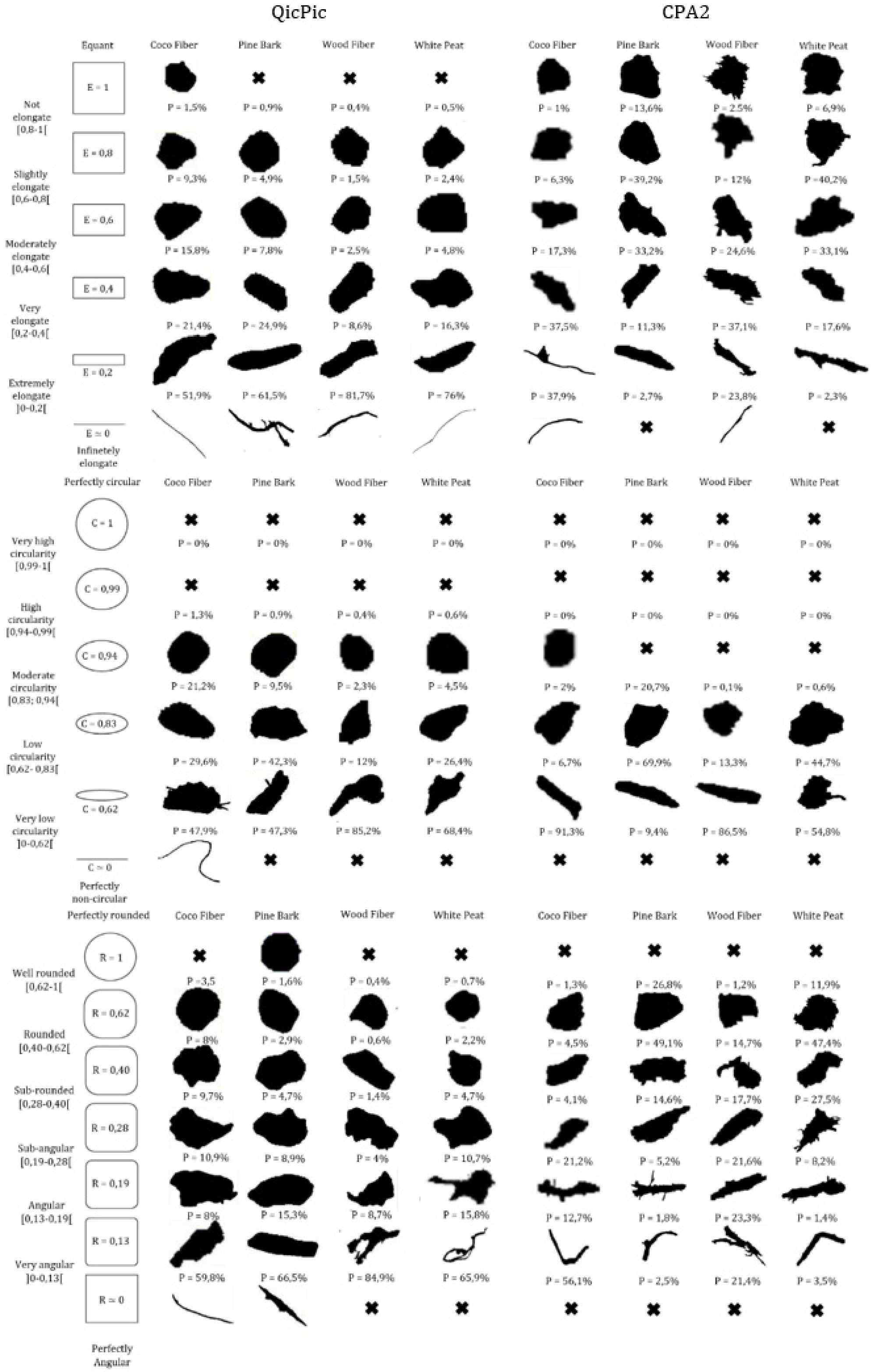

Figure 4. Particle shape distribution for elongation, circularity and roundness, and visual representation for each interval bound, from QicPic (left) and CPA2 (right). Proportion (P=%) corresponds to the frequency of particles by volume included in each interval.

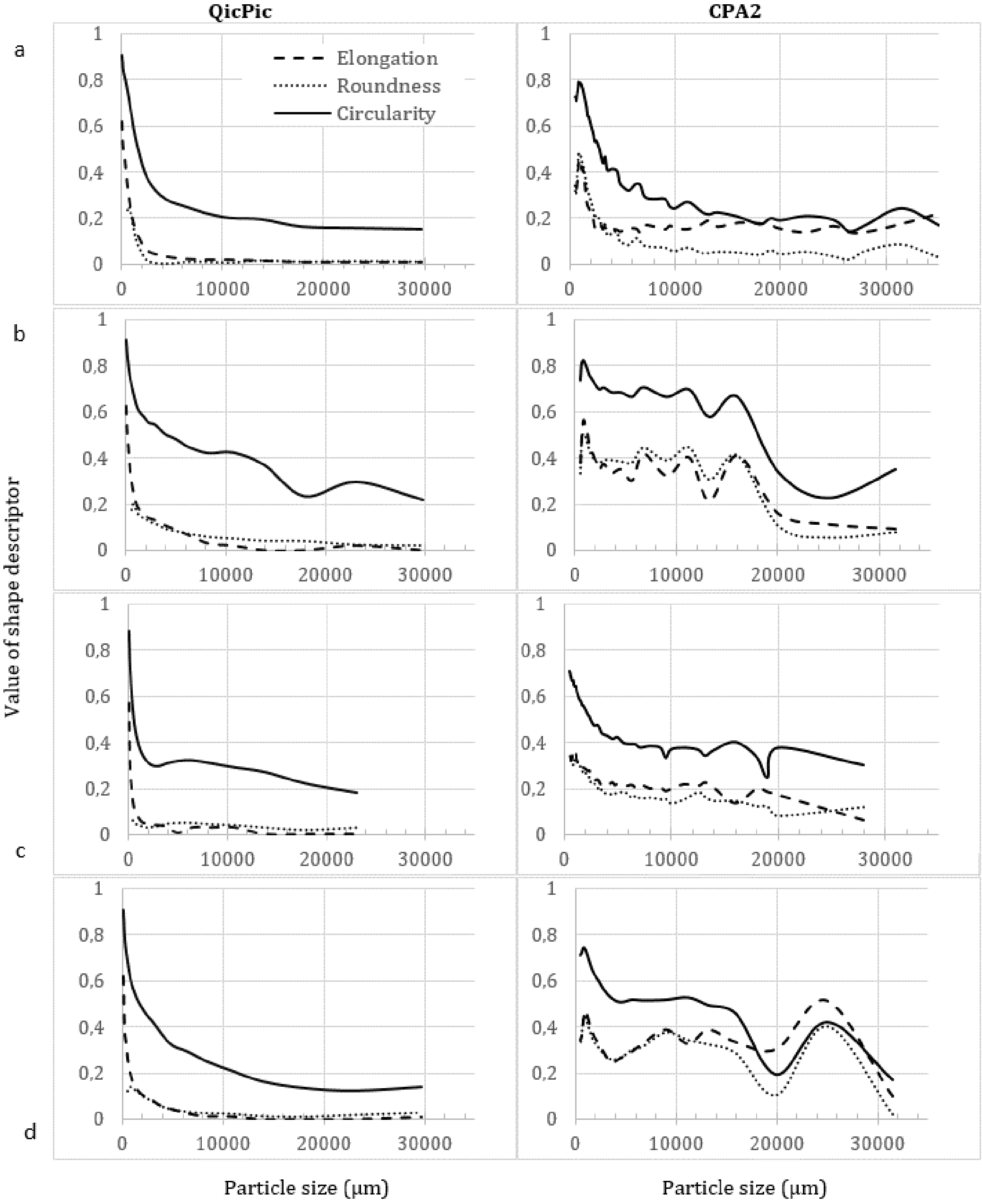

Figure 5. Evolution of shape descriptors as a function of particle size for coco fiber (a), pine bark (b), wood fiber (c) and white peat (d) obtained by the QicPic and the CPA2.

DISCUSSION & CONCLUSIONS

Coco fiber is very to extremely elongate material; it has a moderate to very low circularity and is mainly very angular. Pine bark is diversified considering elongation, has a low to very low circularity and is diversified considering roundness. Wood fiber is a very to extremely elongated material, has a very low circularity and a with a very high angularity according the QicPic, while the CPA2 shows a diversity of roundness. White peat is diversified considering elongation and roundness, its circularity is low to very low. All materials tested here show an increasing elongation and a decreasing circularity and roundness with larger particle sizes.

Differences in the results between both QicPic and CPA2 methods can be explained by

(1) different samples by removing ranges in particle size studied (from 50µm to 33,8 mm for QicPic, and from 0,5 mm to 45 mm for CPA2), (2) calculation models used for particle shape elongation and roundness, and (3) preparations of materials for testing (wet and dry dispersion for QicPic and CPA2, respectively). Despite that, their use showed a certain degree of complementarity, allowing a wide spectrum for particle size and shape distributions.

QicPic is more suitable for materials with high contents of smaller particles in < 0,5 mm particles (up to a maximum of 33,8 mm), and the CPA2 worked with particles above 0.5 mm up to a maximum over 45 mm. Between these two thresholds (from 0,5 mm to 33,8 mm), both tools can be used, but the results should be cautiously analyzed, regarding the different calculation methods likely influencing their interpretation.

Weighting of distribution was approximated using a modeled 3D volume obtained by the modeling of the particle into a sphere according its 2D projected area. This modeling from two to three dimensions does not precisely estimate the real volume of a particle. Also, the particle density can likely vary according to their size, stating that the density is the same for all particle prevent an equal comparison of particle distribution made by sieving.

That being said, both systems were able to image particle shapes of all materials tested. This importance of particle shapes cannot be overstressed. There can be 85-95% pore volumes in horticultural substrates in containers (only 5-15% solids by volume). To improve substrate science, we need to begin to engineer particle shapes and predict the resulting pore shapes and volumes. These techniques begin to provide ways of measuring particle shapes in predictable ways.

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