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Particle size and shape of growing media constituents. Relationships with their physical properties

Stan Durand

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Stan Durand. Particle size and shape of growing media constituents. Relationships with their physical properties. Agricultural sciences. Agrocampus Ouest, 2023. English. NNT : 2023NSARC168 . tel-04769864

HAL Id: tel-04769864

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THESE DE DOCTORAT DE

L'INSTITUT NATIONAL D'ENSEIGNEMENT SUPERIEUR POUR L'AGRICULTURE, L'ALIMENTATION ET
L'ENVIRONNEMENT, DOCTEUR DE L'INSTITUT AGRO, RENNES ANGERS

ECOLE DOCTORALE N° 642

Ecole doctorale Végétal, Animal, Aliment, Mer, Environnement
Spécialité : « *Sciences agronomiques* »

Par

Stan DURAND

Taille et forme des particules des constituants des supports de culture horticoles. Relations avec leurs propriétés physiques.

Particle size and shape of growing media constituents. Relationships with their physical properties.

Thèse présentée et soutenue à Angers, le 2 mai 2023

Unité de recherche : UP EPHor, Environnement Physique de la plante HORTicole

N° d'ordre : 2023-8

N° de série : C168

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Acknowledgments

This work could be realized thanks to the help of many people, whether it is a participation in research activities, financial assistance, training, administrative, or simply for having given me strength, I wish to thank all these people from the bottom of my heart.

Jean-Charles Michel, as Ph. D supervisor, has given me a scientific training, confidence, a network, great human experiences and his support. I am proud of what we have accomplished, working as a team with William Fonteno and Brian Jackson to advance horticultural science. I thank you warmly, for welcoming me in Horticultural Science Laboratory (NCSU, Raleigh, USA) with kindness and the will to make me progress. You have all, in a significant way, contributed to the success of this thesis.

Thanks to Laurent Caner and Pascal Boivin (members of my thesis committee), for giving me a global vision of this work and confidence to move forward.

I am grateful to Isabelle Cousin, Safya Menasseri-Aubry, Jean Caron, Mathieu Javaux and Rémi Naasz for taking time to evaluate my work and participate in my Defense as members of the jury.

This work was made possible thanks to the funds and confidence given to us by the companies and their representatives for this project: Frédéric Dutertre (EVADEA), Nathalie Vialles and Jean Roudier (Klasmann-Deilmann), Philippe Pracht (Floragard), Fabrice Barraud (Premier Tech) and Chris Greenwood (Turf Tech Ltd). As well, I proudly thank the French public institutions Région Pays de la Loire and Angers Loire Métropole for providing funds for this project. Then, I am very grateful to the Doctoral school EGAAL for giving me training and support. Finally, the Fulbright Program for their financial and administrative support during my stay in the United State of America.

During those three years in L'Institut Agro – EPHor research unit, I have been greatly helped with technical support by Céline Levron, Yvette Barraud-Roussel, Claudie Mazzega, Joel Blochas, Bruno Cannizzo, Michel Dubois, Cassandra Catrouillet, Marc Ballan, Anne De Guibert, Hugo Mussard and Yvan Barraud; scientific engineering by: Dominique Lemesle, Lydia Brialix, Ewans Brouch and François Ortiz. Literature ressources by Francoise Le Tohic and Béatrice Lacoste; administrative support by: Christine Durand, Marie-Pierre Louage, Sylvie Guyader and Isabelle Baumgarten.

This experience brought me to meet some nice people that gave many considerations for our project, thank you to them: Thorsten Kraska, Bart Vandecasteele, Laurent Largant, Winfried Timming, Jeb Fields, Vincent Guillotin., Neil Bragg, Sebastian Kipp, Matthieu Carof, Frederic Debesse, Pascal Courtabessis, Jean-Marie Andigane, Soulaïman Sakr, Brian Schulker, Cédric Deluz and Dorine Cannone. Among these new meeting, I would like to thank especially Van Nguyen, Paul Bartley and Bill Fonteno (again), for giving me a lot of their time to help me improve my work and also for the constructive exchanges we had.

Shout out to my close relations who gave me strength and who also opened and comforted me to direct me towards the vegetable productions, but also contributed in various scale to the achievement of this work: Edwige, Jean-Marc, Lou, Tom, and other members of the Durand and Ossart families, Tanguy Balanant, Thibaut Derrien, Mael Rebelo, Clément Leroy, Florian Saas and Luciana Salinas.

I am deeply grateful to all these people mentioned, I wish you the best and that our paths cross again.

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General introduction

General context of the work: soilless horticultural production and use of growing media

Growing plants in containers rather than in mineral soil (soilless culture other than soil *in situ*) is one of the most promising solutions to: 1) meet increasing food needs with the continuing rise in population and concomitant decrease in arable land (Raviv & Lieth, 2008), and 2) to help in the revitalization of overused land subjected to poor human stewardship. The advantages of soilless production over open field-grown crops are numerous, including increased water and nutrient use efficiency, higher yield and quality, more precise pest and disease control, etc. Soilless production is increasing in greenhouse vegetables but is receiving more attention in greenhouse fruit production, as well as open field production of ornamental, vegetable and fruit crops in containers. As the demand for soilless horticultural products increase, so does the need for new and improved raw materials as reliable components of growing media. In 2017, the global market for growing media represented a volume of 67 million cubic meters (Mm³); by 2050 this volume is estimated to reach 283 Mm³ (Table 1, Blok et al., 2021).

Table 1. Total estimated market in 2050 based on the expected market increase and a more realistic estimate of the potentially available materials (Blok et al., 2021).

	2017 (Mm ³ .year ⁻¹)	2050 (Mm ³ .year ⁻¹)	Increase (%)
Peat	40	80	200
Coir	11	46	418
Wood fiber	3	30	1000
Bark	2	10	500
Compost	1	5	500
Perlite	1.5	10	667
Stone wool	0.9	4	433
Soils/tuffs	8	33	413
New		65	
Total	67	283	422

A growing medium is defined as a material other than soil *in situ*, in which plants and mushrooms are grown (CEN 2022). Its functions are to offer physical, chemical and biological support, to store and exchange nutrients, water and gases (Caron & Zheng, 2021) and to provide a medium to develop a root architecture for good plant growth and plant development. The choice of growing media (*i.e.*, its constituents and their proportion) depends on: 1) the growing system and, in particular, on the requirements of the plant, 2) the species and its phenological stage (Lemaire, 1989), 3) the irrigation strategy and systems (drip, ebb and flood, sprinkler), and 4) on the fertilization strategy (continuous or punctual fertigation, coated solid fertilizers, etc.) (Figure 1). The success of a soilless culture depends on proper application of irrigation and fertilization according to the properties of the growing media. Crop failure is often caused by poor irrigation management, which can lead to: 1) asphyxiation

of the root system, 2) nutrient leaching, 3) physiological stress of the plants and 4) acquisition of a hydrophobic character of organic materials in the dry conditions (Michel et al., 2001).



Figure 1. Raspberry crop in coir (Panach'fruits, Saint-Hilaire-la-Forêt, France) and tomato crop in stonewool in greenhouses (Klein-Atendorf Campus, Bonn, Germany), equipped with a drip fertigation system.

Beyond agronomic criteria, growing media constituents are selected according to their availability, cost and, more recently, by environmental impact criteria (e.g., harvest methods, source location in environmentally sensitive areas, and carbon foot print). The availability of raw materials is different from one place in the world to another, depending on the proximity of the resource to manufacturing locations, the purchasing capacity, supply and logistics of the growing media manufacturer. Today, manufacturers are making great efforts to increase the supply of raw materials and find new ones, that are agronomically efficient, sustainable and relatively low cost. They are looking to promote peat alternatives while competing for these alternatives with other industries (like wood products).

Most of growing media constituents are derived from plant materials. Among them, peats (especially *Sphagnum sp.* mosses (Figure 2)) are one of the main constituents used all over the World, representing approximately 75% vol. of the total market in Europe (Schmilewski, 2017; Jackson, 2021) and 60% in France (Michel & Largant, 2022) (Figures 3 & 4), mainly due to their positive physical properties (water retention, physical stability) (Michel, 2010). However, this carbonaceous fossil resource has limited sustainability with resources depleting at a fast rate in many parts of the world. This is coupled with the peat resources, which are generally found in swampy bogs (Figure 5) being declared wetlands that represent an important carbon sink at the global scale and then need environmental protection. Societal demand and ecological policies are therefore aiming to limit the use of these peatlands, to move towards a wiser use of peat (Clarke, 2008), and to promote renewable organic materials as growing media (Jackson, 2021).



Figure 2. Fresh *Sphagnum sp. moss*, Geeste, Germany.

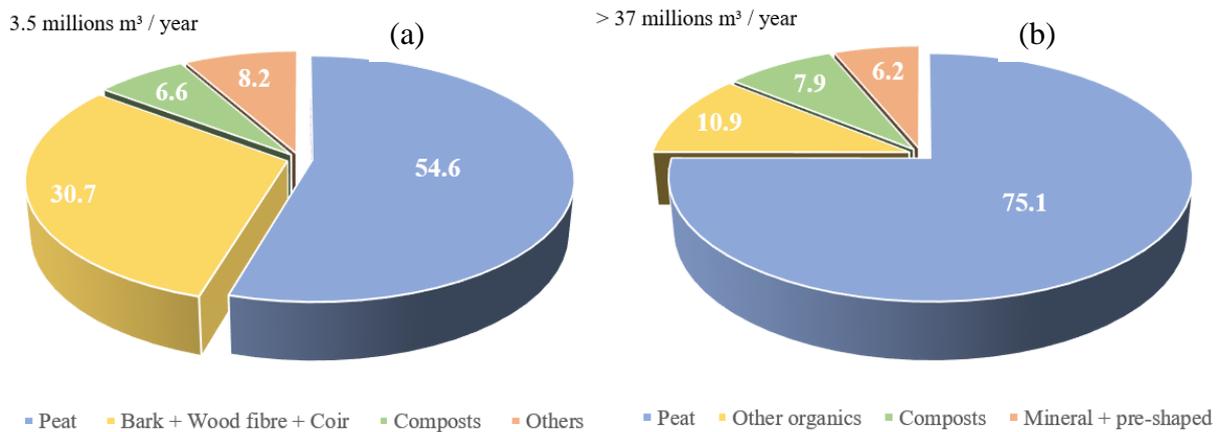


Figure 3. Proportions of raw materials used as growing media in France (a) and in Europe (b). From Largent & Michel (2022) and Schmilewski (2017).

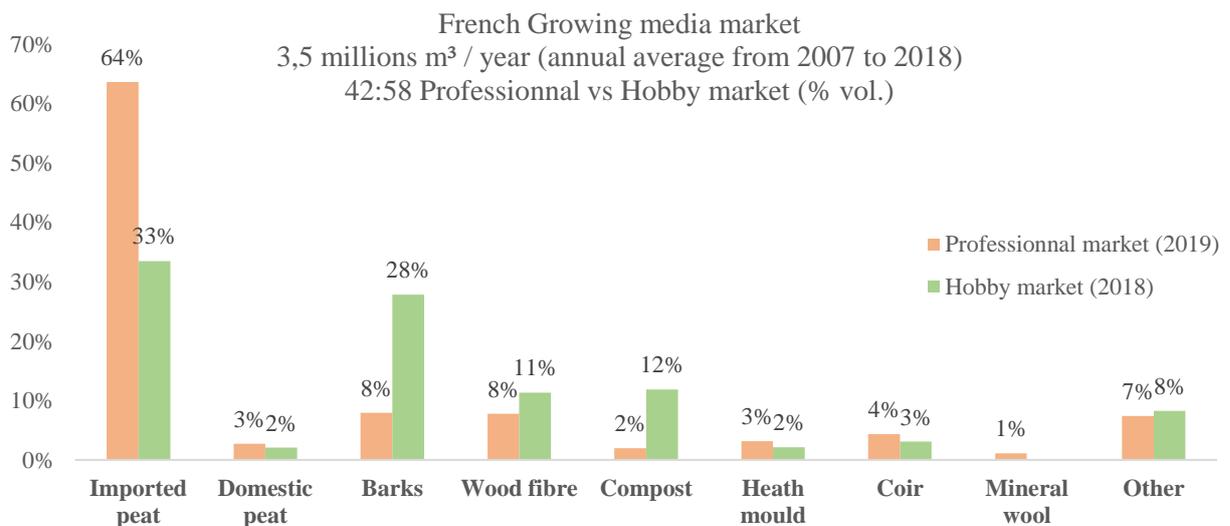


Figure 4. Raw materials used as growing media constituents in France for professional and hobby markets in 2019 and 2018, respectively (Largent & Michel, 2022).



Figure 5. Peat bog (a), peat exploitation (b), peat shipping by boat (c) - (pictures belong to Klasmann-Deilmann).

Other materials most commonly used as growing media constituents are coir (from coconut husk), wood fibers, tree barks (composted, aged or fresh) and traditional composts (Schmilewski, 2017; Largent & Michel, 2022) (Figures 3 & 4). Other more marginal and/or crop-specific materials include stone wool (as a "bat or loaf"), biochars, perlite, sand, pozzolan and other minerals.

Physical properties of growing media

Parameters used to describe the static physical properties of growing media

The physical properties of a growing media are often characterized by a water retention curve (Figure 6) according to standardized procedures (AFNOR, EN13041, 2000), from which static parameters have been defined to assess the availability of air and water for the plant, and to manage irrigation (De Boodt & Verdonck, 1972):

- total porosity, corresponding to the proportion of the total bulk volume available for storing water and/or air;
- air-filled porosity (AFP), corresponding to the proportion of air that has replaced water initially occupying coarser porosity that has rapidly drained (usually measured at water potentials < -1 kPa);
- water holding capacity (WHC, also called container capacity), corresponding to the proportion of water retained when air occupies coarser porosity that has rapidly drained (usually water potentials < -1 kPa);
- easily available water (EAW), referring to the proportion of water released between container capacity (-1 kPa) and -5 kPa;
- water buffering capacity (WBC), referring to the proportion of water released between -5 and -10 kPa, and that enables the physiological adaptation of the plant to the increase in water potential (De Boodt & Verdonck, 1972).

It is commonly reported that a growing media should offer $AFP > 20\%$ vol., WHC varying between 55 and 65% vol., and EAW varying between 20 to 30% vol. (Raviv & Lieth, 2008, Morel et al., 2000).

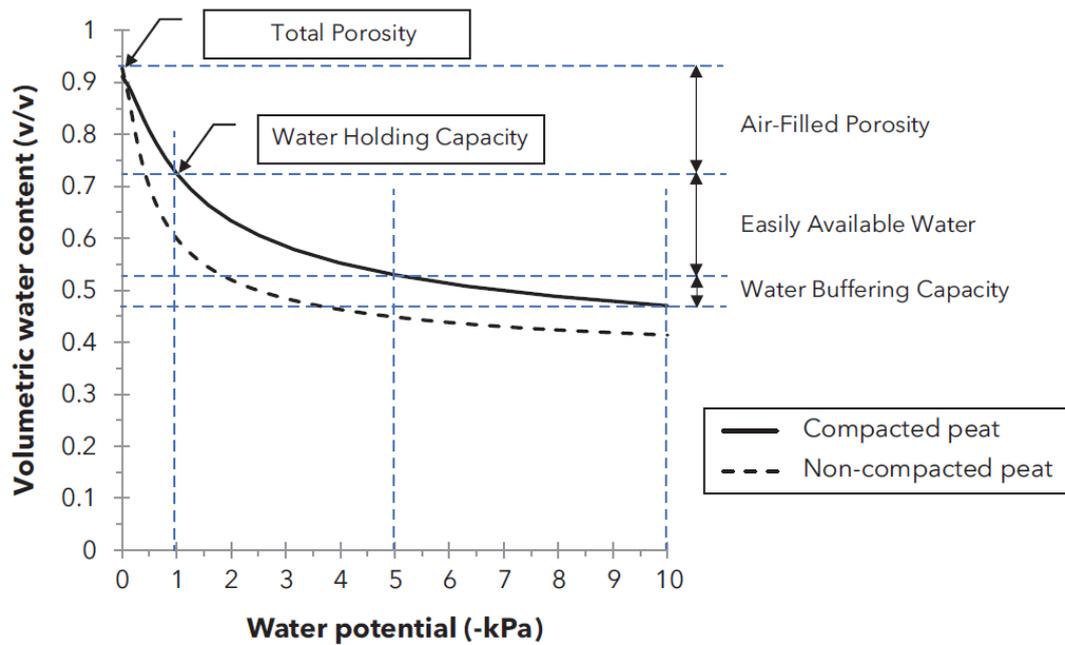


Figure 6. Water retention curves for a compacted- and a non-compacted white milled peat, with graphical identification of the main physical parameters for compacted peat. (Caron & Michel, 2021).

These basic parameters are sometimes (or rather, should be more generally) complemented by dynamic measurements of water and air flow properties (Caron et al., 2008) and wettability (Michel, 2015), from which thresholds for the bioavailability of water and oxygen in the growing media have been defined, allowing to refine irrigation management (Table 2).

Table 2. Criterion used to evaluate growth limitations in growing media. (Caron & Michel, 2021).

Parameters	Aeration		Water			
	Air-filled porosity at -1 kPa	Gas diffusivity	Available water (from -1 to -10 kPa)	Ks	α	Wettability(θ)
units	cm ³ cm ⁻³		cm ³ cm ⁻³	cm s ⁻¹	kPa ⁻¹	°(degrees)
static	0.15-0.40 ^{a,b,c}		0.20-0.30 ^b			<90 ^b
dynamic		0.010-0.015 ^d 0.003-0.005 ^e		0.08 ^f		<87 ⁱ
					9.6 ^g	

Ks and α are unsaturated hydraulic conductivity curve parameter, and θ is the contact angle.

^a From Wever (1994).

^b de Boodt and Verdonck (1972).

^c Naasz et al. (2008).

^d From Allaire et al. (1996) for -0.8 kPa in 5, 9 and 14 L nursery container.

^e From Boudreault et al. (2014) for -0.6 kPa in tree seedlings.

^f Mustin (1987).

^g Caron et al. (2005a).

^h From Michel et al. (2001).

ⁱ From Michel (2015).

Factors explaining substrate physical behavior: the importance of particle size

As for soils, solid phase and pore phase organization and, consequently, physical properties, are in part influenced by their PSD, but many other factors/process affect water and air retention and flow properties, as well as shrinkage properties (Caron & Michel, 2017), such as:

- mixing and potting operations (Gruda & Schnitzler, 2004);
- the container geometry (Bilderback & Fonteno, 1987; Raviv et al., 2002; Owens & Altland, 2008);
- the repeated drying (due to plant uptake and evaporation) and rewetting (during irrigation), and the intensity of drying (Naasz et al., 2008; Qi et al., 2011);
- the decomposition of the materials due to the activity of microorganisms and chemical effect such as change in the pH (Domeño et al., 2011);
- settling during cultivation, increasing the bulk density then reducing the total porosity (Jackson et al., 2009);
- root development, by progressively filling the macroporosity (Allaire et al. (1999), Nkongolo & Caron (2006), Caron et al. (2010), Cannavo & Michel (2013), Kerloch & Michel (2015), Michel & Kerloch (2017), and Michel (2019)).

In any case, growing media manufacturers engineer and select the particle size of growing media constituents to provide the plant root system a suitable physical environment, assessed from parameters resulting from the water retention curves. For that, different mechanical processes are implemented by the growing media industry (Figures 7 and 8): 1) separation by sieving and/or screening, 2) grinding, 3) cutting, and or 4) defibration or expansion of the raw materials. These actions result in the production of particles with predefined size ranges, and also modify the shape and surface aspects of the particles.



Figure 7. Defibration of wood pellets (a) into wood fiber (c) using a defibration tools (b).

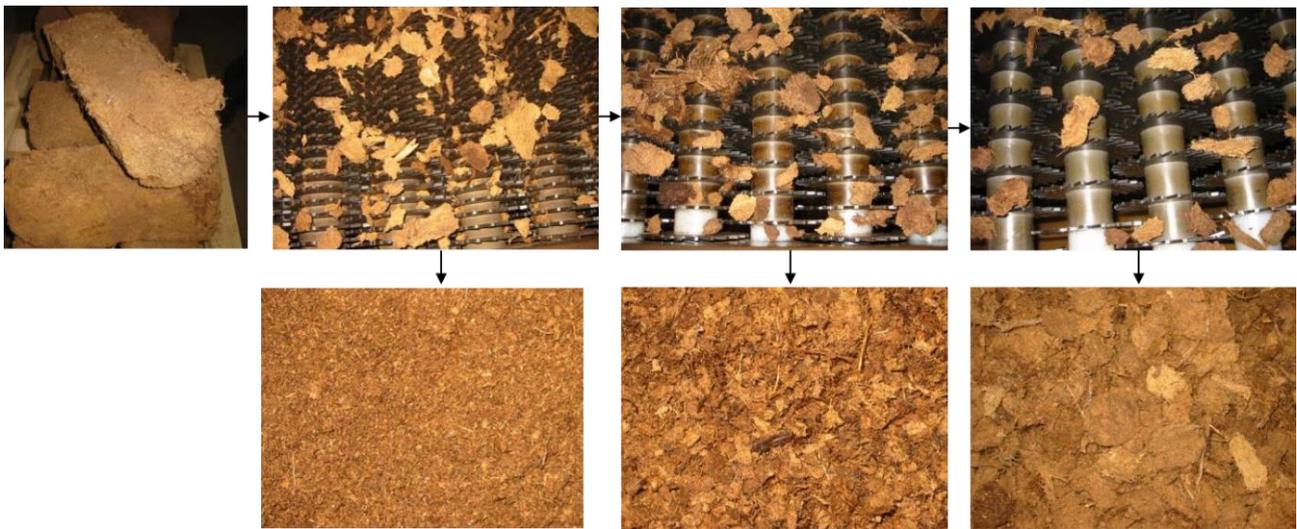


Figure 8. Sod peat processing through star screen, producing 7-12 mm, 12-25 mm, and 25-45 mm particle size fractions (pictures provided by Klasmann-Deilmann).

To analyze particle size distribution, researchers and manufacturers use various sieving procedures (ISO, 1988; AFNOR, 2007). Sieving has the advantages of being low cost, quite fast and mastered by the entire horticultural industry. Consequently, relationships between particle size and physical properties carried out on growing media have been based on different sieving procedures (ISO, 1988; AFNOR, 2007), concluding that the larger the particle size, the higher the resulting air-filled porosity and the lower the water retention properties (Bunt, 1983; Handreck, 1983; Abad et al., 2005; Caron et al., 2005; Owen & Altland, 2008; Fields et al., 2014; Nguyen et al., 2022).

However, sieving also present multiple limitations to describe the particle morphology (Igathinathane et al., 2009; Gil et al., 2014; Bartley et al., 2022), mainly because it separates particles by their width, and then is much less accurate for non-spherical particles, like many of growing media constituents (barks, fibers, for example).

Recently, the use of dynamic image analysis (DIA) tools has been introduced for the morphological characterization of materials used as growing media components (Bartley, 2019; Nguyen et al., 2022) (Figure 9 & 10). These tools allow to describe particle size along several dimensions (width, length, surface area), but also particle shape (circularity, elongation, roundness *etc.*). Investigating particle size and shape is then highly relevant for growing media, having particles with a wide range of sizes (from a few μm up to 20-25 mm) and shapes (fibers, chip, grains, *etc.*) that assemble to create a much higher porosity (usually $> 85\%$ in volume) than that in most soils. Hence, particle size and shape greatly influence the structure of the resulting materials, and thus their physical properties, so that the use to image analysis tools can help to improve the understanding of the relationships between particle morphology and the physical properties of growing media (Bartley, 2019; Durand et al., 2022).

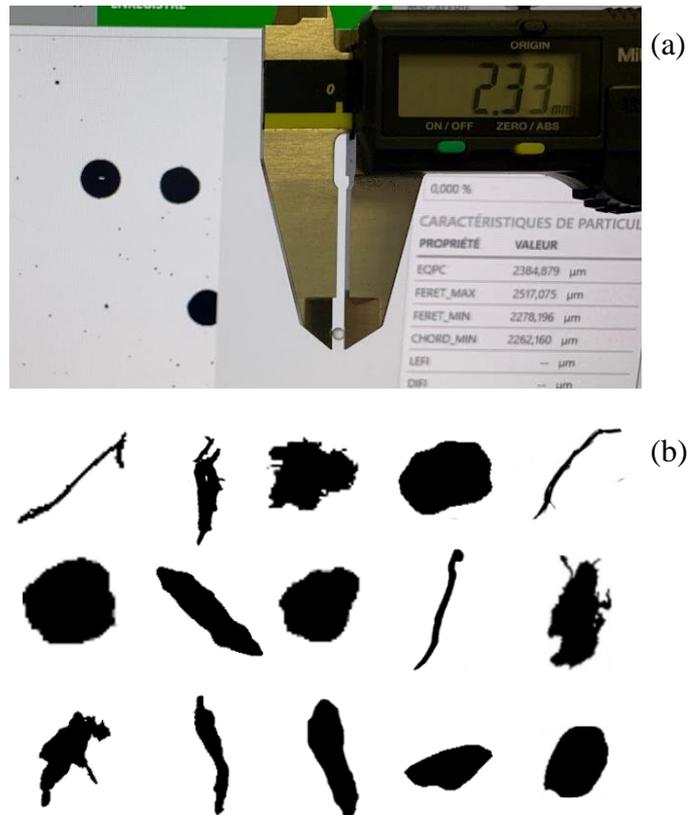


Figure 9. Plastic bead diameter measurement in agreement with image analysis measurement (a); pictures of various materials particle taken by the QicPic device (b).

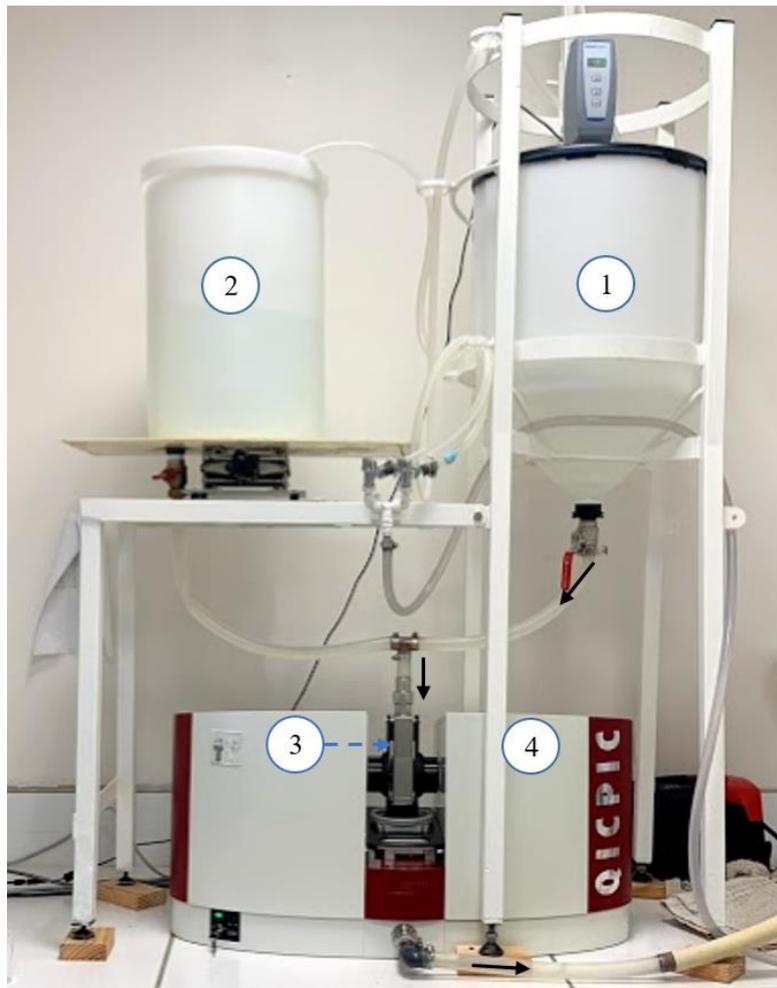


Figure 10. QicPic and associated set-up used for particle morphology characterization by dynamic image analysis. 1) water tank containing particles, equipped with an agitator; 2) water tank used to control the concentration of particles; 3) cell where particles are contained/pass for the measurement; 4) camera position of the device. Black arrows indicate the particle-water flow, regulated by a peristaltic pump.



Figure 11. Shrinkage properties measurement with HyProp systems (Hyprop II, Meter Group Inc., USA) coupled with LVDT determining continuously water content, water potential and changes in total volume.

Goals of the work & Manuscript outline

The general aim of the work was to: 1) precisely describe particle morphology of growing media constituents (texture), 2) to ascertain particle arrangement (structure) and 3) predict their associated physical properties according to texture.

In details, this manuscript is subdivided into **five parts**, corresponding to **five papers**, whose:

- Papers 1 & 2 are **already published in peer-review journals** (Soil Science Society of America Journal, and in the Special issue “*Advanced Research on Soilless Culture in Horticultural Production*” of Agriculture),
 - Paper 4 is **published in Acta Horticulturae proceedings**, and
 - Papers 3 & 5 are **close to submission to peer-review journals**: Soil Science Society of America Journal for paper 3, and Scientia Horticulturae for paper 5, are envisaged.
- **Paper 1** aimed to identify relevant descriptors to assess the particle size using Dynamic Image Analysis, and also to compare particle size distribution obtained by this innovative DIA method with the standardized sieving procedure.
- **Paper 2** aimed to finely analyze particle shape as well as particle size, and to propose a first classification of growing media constituents, based on both particle size and shape.
- **Paper 3** aimed to analyze and explain the influence of particle morphology on the particle arrangement (structure), through the shrinkage curves analysis of raw materials and derived size fractions (Figure 11).
- **Paper 4** aimed to bring out a general relationship between particle size and water holding capacity for a large panel of growing media constituents, according to different size indicators (*i.e.*, mean particle length, mean particle width, and mean weight diameter).
- **Paper 5** aimed to assess relationships between particle size fractions and physical properties, while identifying the most relevant size descriptor to predict physical properties of raw materials from those of derived size fractions.

Panel of materials studied

Works presented in this manuscript were carried out on a large panel of materials, for a total of 30 studied materials (Figure 12), representing the diversity of growing media constituents available in the global market. These references include:

- **14 peat samples**, with:
 - **11 Sphagnum white peat**, *i.e.*, **weakly decomposed** peat, differing by the selected particle size, country of origin, and methods of extraction (milling peat presenting fine and separated materials, sod peat designing some aggregates);
 - **2 Sphagnum black peat**, *i.e.*, **highly decomposed** peat, from different countries;
 - **1 Sedge brown peat**, **moderately decomposed**;
- **6 pine bark** samples, with 3 particle size fractions of **fresh** and **composted** pine barks;
- **3 wood fiber** samples, differing by their selected size fractions, and processing methods;
- **4 coir products** resulting from the grinding and sieving process of coconut husk, leading to **coir**, **coir fiber**, and **coir pith** (respectively, number 9 & 10, 11 and 12 on Figure 11). Fiber and pith being two different components of the husk, coir is the raw product, not sieved;
- **1 green compost** sample;
- **2 perlite** samples, differing by their particle size fractions.

Throughout the various papers in this manuscript, different sets of materials are used. The list of materials, by number (Figure 12) per papers is as follows:

- **Paper 1:** 4, 7, 12, 16, 19, 29
- **Paper 2:** 1, 4, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 22, 23, 24, 25, 28, 29, 30
- **Paper 3:** 4, 8, 9, 23, 29
- **Paper 4:** 1, 4, 7, 8, 9, 12, 13, 14, 15, 16, 19, 20, 22, 23, 24, 25, 28, 29, 30
- **Paper 5:** 4, 8, 9, 23, 29

Note that materials 2, 3, 5, 6, 26 & 27 (Figure 12) do not appear in these papers, as their coarse particle size did not allow their characterization by image analysis





Figure 12. Raw materials selected: 1. Composted pine bark 'fine', 2. Composted pine bark 'medium', 3. Composted pine bark 'coarse', 4. Fresh pine bark 'fine', 5. Fresh pine bark 'medium', 6. Fresh pine bark 'coarse', 7. Baltic black peat, 8. German black peat, 9. Coir (Ivory Coast), 10. Coir (Sri Lanka), 11. Coir fiber, 12. Coir pith, 13. Green waste compost, 14. Sedge peat, 15. Perlite 'fine', 16. Perlite 'coarse', 17. Canadian white milled peat (east), 18. Canadian white milled peat (west), 19. Irish white milled peat, 20. Latvian white milled peat 'fine', 21. Latvian white milled peat 'medium', 22. Lithuanian white milled peat, 23. Lithuanian white milled peat 'medium', 24. Lithuanian white sod peat, 25. German white sod peat 'fine', 26. German white sod peat 'medium', 27. German white sod peat 'coarse', 28. Wood fiber 'fine' (Greenfibre), 29. Wood fiber 'medium' (Greenfibre), 30. Wood fiber 'fine' (Florafibre).

Five of these raw materials (*i.e.*, one sample of white peat, black peat, fresh pine bark, wood fiber, and coir) were also fractionated into particle size fractions by wet sieving (Figure 13) to conduct more detailed analysis of texture, structure, and resulting physical properties of each particle size fraction (see Papers 3 & 5). These other 29 references are presented in Figure 14.



Figure 13. Wet sieving procedure for collecting derived particle size fractions from raw materials.

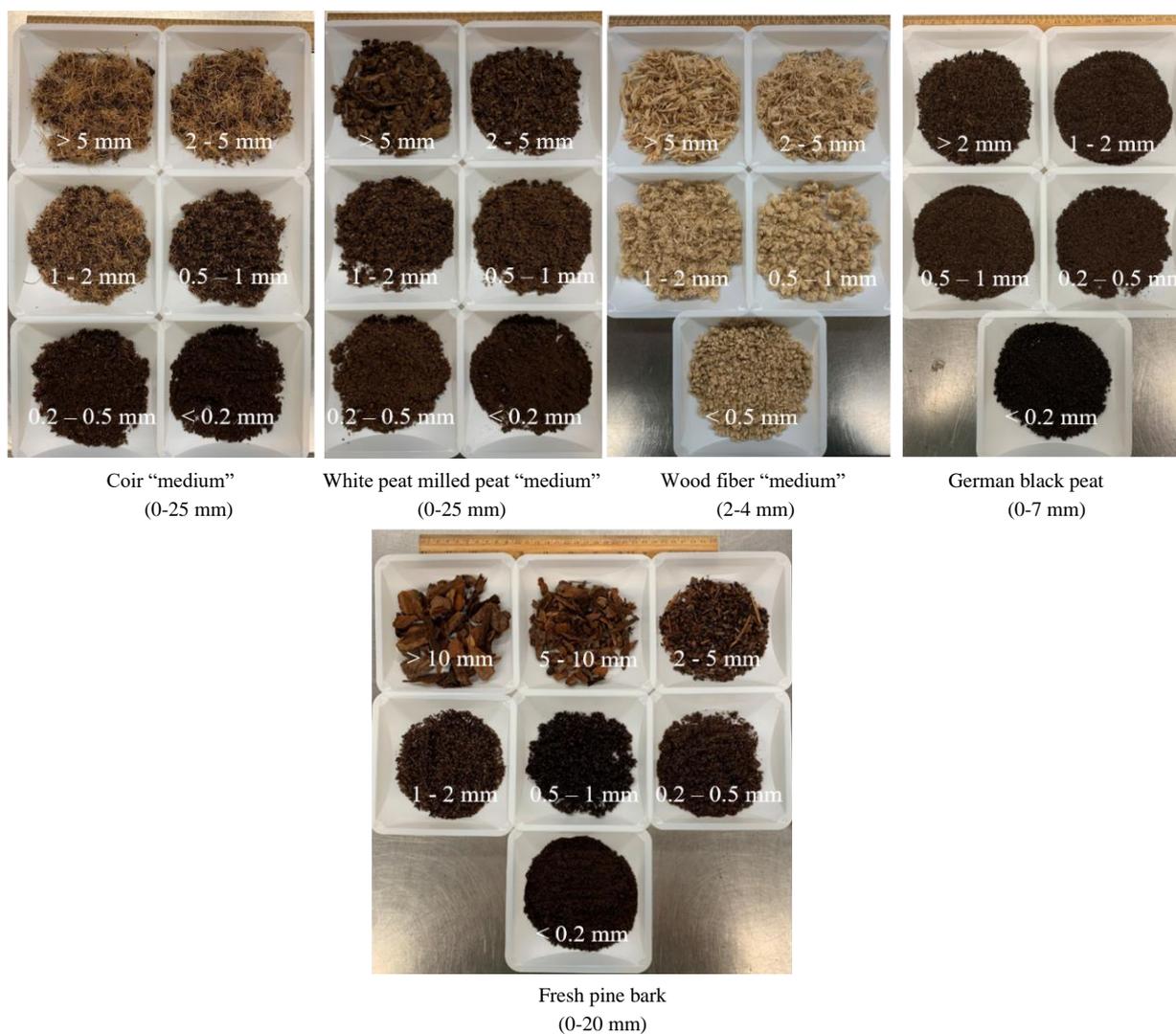


Figure 14. Fractionated materials studied.

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Part I: Particle Morphology Characterization

Lists of materials studied (material pictures in General Introduction, Figure 12)

Paper 1

4. Fresh pine bark 'fine'
7. Baltic black peat
12. Coir pith
16. Perlite 'coarse'
19. Irish white milled peat
29. Wood fiber 'medium' (Greenfibre)

Paper 2

1. Composted pine bark 'fine'
4. Fresh pine bark 'fine'
7. Baltic black peat
8. German black peat
9. Coir (Ivory Coast)
10. Coir (Sri Lanka)
11. Coir fiber
12. Coir pith
13. Green waste compost
14. Sedge peat
16. Perlite 'coarse'
17. Canadian white milled peat (east)
18. Canadian white milled peat (west)
19. Irish white milled peat
20. Latvian white milled peat 'fine'
22. Latvian white milled peat 'medium'
23. Lithuanian white milled peat
24. Lithuanian white milled peat 'medium'
25. Lithuanian white sod peat
28. Wood fiber 'fine' (Greenfibre)
29. Wood fiber 'medium' (Greenfibre)
30. Wood fiber 'fine' (Florafibre)

Paper 1: Particle Size Distribution of Growing Media Constituents Using Dynamic Image Analysis: Parametrization and Comparison to Sieving

Durand S., Jackson B.E., Fonteno W.C., Michel J.C., 2022. Particle size distribution of growing media constituents using dynamic image analysis: parametrization and comparison to sieving. *Soil Science Society of America Journal*, <https://doi.org/10.1002/saj2.20518>

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 sieving DM and HM methods.

This work suggests the relevance of two parameters, Feret_{MAX} and Chord_{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 in 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.

Abbreviations: DIA, Dynamic Image Analysis; Feret_{MAX}, Maximum Feret diameter; Feret_{MIN}, Minimum Feret diameter; Chord_{MIN}, Minimum chord diameter; MIC, Maximum Inscribed Circle; PSD, Particle Size Distribution; Sieving Dry Material: Sieving DM; Sieving Hydrated Material: Sieving HM

Introduction

Particle size and physical properties

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 physical properties (Handreck, 1983; Verdonck & Demeyer, 2004; Caron et al., 2005; Raviv et al., 2019; Bartley et al., 2022). 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 lower the water retention properties (Bunt, 1983; Handreck, 1983; Abad et al., 2005; Caron et al., 2005; Fields et al., 2015; Owen & Altland, 2008; Nguyen et al., 2022).

Methods of PSD analysis: benefits and limits

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, 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 axes dimension, except for spherical-like particle. Sieving procedures segregate particle according to their 2nd largest dimension, *i.e.*, their width (Igathinathane et al., 2009; Ulusoy & Igathinathane, 2016; Bartley, 2019), also called true sieve size (Allen, 2003), except for particles with very low thickness where the diagonal aperture size should be considered (White, 2003; Gil et al., 2014). Gil et al. (2014) reported on poplar and corn stover (which are elongated and curved materials) a sieving efficiency of 70% in comparison with 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 raw materials used as growing media constituents are derived from decaying organic matter (Durand et al., 2021b), which are characterized by a large diversity in particle size and shape. 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 (Liu, 2009; Bartley, 2019). Standard methods are based on the use of dry materials: oven dried at 40°C (AFNOR, 2007), or 105°C (ISO, 1988) 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, 1984) that cannot be disaggregated during the sieving process. Also, some materials are friable and may be broken 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.

Methods of wet sieving have also been developed (Yoder, 1936; Levesque & Dinel, 1977; Robertson et al., 1984; Allen, 1997; Nemati et al., 2009), and revealed a higher content of fine particles than by sieving dry material (Levesque & Dinel, 1977; Robertson et al., 1984; Nemati et al., 2009). The water helps aggregate dispersion, *i.e.*, thus particle individualization (ISO, 1988), and favor 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 the 80s for various industrial and research applications, and are now widely used, like the laser diffraction method (Yang et al., 2019; Polakowski et al., 2021) for soil particles usually ranged from 0.02 μm to 2 mm (Blott et al., 2004; Keck and Muller, 2008; Polakowski et al., 2021). For larger particle ranges like growing media constituents, dynamic image analysis (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 Bartley (2019) and Durand et al. (2021b), who initiated a first description of some raw materials from DIA. Figure 1, below, highlights the particle shape diversity for the study materials.

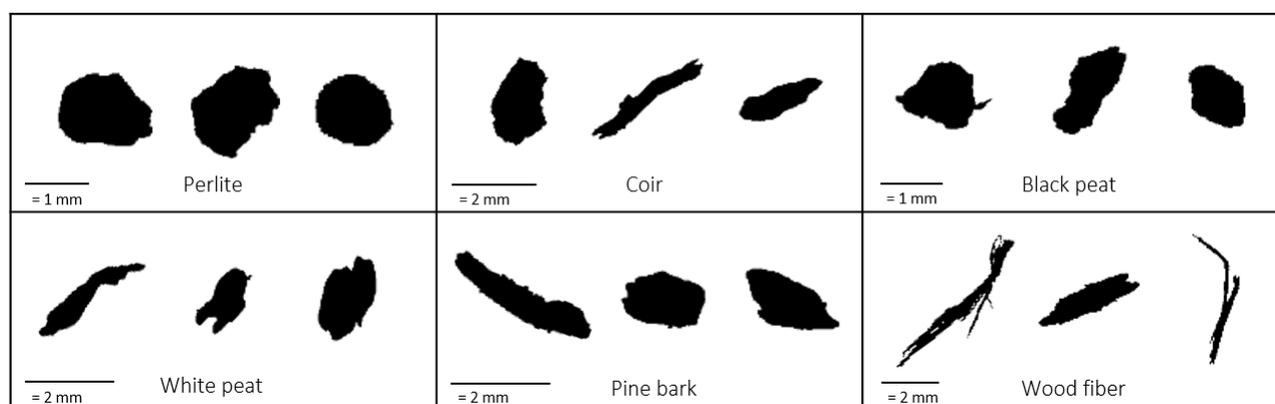


Figure 1. Images of representative shape of the particles provided by the QicPic device.

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

In comparison with sieving, data collected with DIA offer more detailed information about each individual particle. DIA accuracy is not limited by a finite set of size class which is the case for sieving where the accuracy of the PSD depending 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 are weighted by number of particles, size, projected surface area or modeled volume of the particles.

Objectives

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. The irregular sizes and shapes of these organic materials fall together to create a pore size arrangement and distribution much larger than in mineral soils, over 80% by volume (Drzal et al., 1999), so that particle size and shape greatly influence the resulting matric structure of the materials, and therefore their physical and hydraulic properties (Raviv et al., 2019). A better knowledge of particle morphology is then of major importance for improving water management and efficiency in soilless horticultural productions, 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 goal of this paper was:

- 1) to determine PSD of some main growing media components with various particle sizes and shapes by three methods: 1) sieving dry materials, 2) sieving hydrated materials, and DIA;
- 2) to compare PSD obtained by dry and hydrated sieving procedures with particle width and length distributions assessed by DIA using several size descriptors (Feret_{MIN}, Chord_{MIN}, bounding rectangle Br_{MIN}, and maximum inscribed circle MIC, for particle width, as well as Feret_{MAX} for particle length);
- 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.

Materials and methods

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 2021b), and also by their different water and air retention properties. Information about these materials are presented in Table 1.

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

Materials	Supplier ¹	Origin	Extraction / process	Indicated	Bulk	Air	Water
				PSD ³	density ²	Filled	Holding
				mm	g cm ⁻³	Porosity	Capacity
						(AFP) ²	(WHC) ²
						% vol.	
White peat, H5 ⁴	PTH	Ireland	Milled, screened	0-5	0.10	11.7	82.3
Black peat, H6-H8 ⁴	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

1: KD = Klasmann-Deilmann, PTH = Premier Tech Horticulture France

2: measured through EN 13041 procedure (2000)

3: PSD indicated by the suppliers

4: Von Post degree of humification

Sieving procedures

Sieving dry materials – Standardized method

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

Sieving hydrated materials

Sieving hydrated materials (HM sieving) was performed with the same set of sieves, same volumes of materials and a same duration experiment, as sieving DM methods. Experiments were carried out on materials at the moisture content they are conditioned in bags by the suppliers, without prior drying: 2.57, 4.60, 0.96, 1.94, 0.43, 0.01 gram 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 is rinsed with water (approximately 1 liter) on the column using a showerhead for a few seconds. The materials retained on each sieve were collected in aluminum cans, placed in the oven at 105°C for 48 hours, then weighted.

Dynamic image analysis

Dynamic Image Analyzer 'QicPic'

DIA was performed with the QicPic (Sympatec GmbH, Clausthal-Zellerfeld, Germany) 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 is less complete. The device is equipped with

a high-resolution camera, capturing images from 17 μm to 33.8 mm. Sample materials are transferred from pipes (20 mm diameter) connected to a 15 liter- hydration tank containing the material to be analyzed. Prior to measurement, material is agitated with a three-armed cone-shaped agitator (VJ100 Visco Jet, Küssaberg, Germany) for 10 minutes to separate the particles without cutting them. The stirring process is maintained during measurement to prevent both particle flotation and sedimentation in the tank. Three replicates per material were measured, with 1 to 2 grams of material per replicate, depending on particle size, density and initial moisture content. This amount of material is defined to maintain an optimal optical concentration of $\sim 1.5\%$, 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 minutes 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 modelling (Li & Iskander, 2020), in order to minimize the discrepancy in the modeling of volume due to shape variability.

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). 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.
- Bounding Rectangle 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.

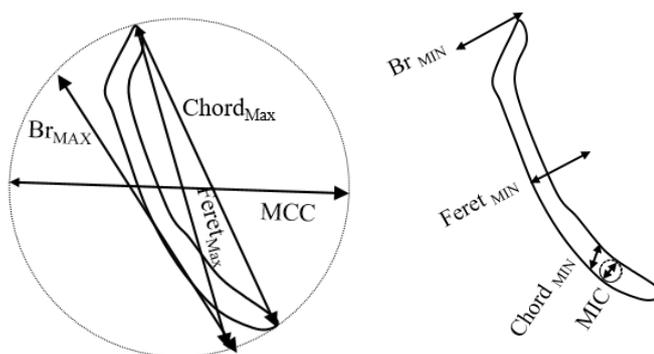


Figure 2. *Diameters measured from Dynamic Image Analysis.*

Particle length determination

As for particle width, there are many diameters that can be used as particle length descriptor. Four have been assessed by DIA, they are described below and on Figure 2. They are similar to those describing the width described earlier.

- Chord_{MAX}: the maximum chord length among all chord measured.
- Feret_{MAX}: the longest distance between two parallels tangent to the particle contour (Figure 2), considered as the longest caliper distance.
- Bounding Rectangle_{MAX} (Br_{MAX}): the length of the smallest rectangle that enclose the particle.
- Minimum Circumscribed Circle (MCC): the diameter of the minimum circle that encloses the particle.

In contrast to the diameters describing the width, these four diameters seem to describe the same dimension with some small variations (Figure 2).

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, 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 & 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 (ANOVA) and Tukey's Honest Significant Difference (Tukey HSD) for mean comparison with 'diameters' as qualitative variable and 'mean size' as quantitative variable.

Results

DIA Width Assessment

In general, the width diameters values ranged in ascending order as follow: MIC \leq Chord_{MIN} \leq Feret_{MIN} = Br_{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 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.

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	Size at the 10 th percentile (D ₁₀)	Size at the 50 th percentile (D ₅₀)	Size at the 90 th percentile (D ₉₀)	Arithmetic mean size		
µm							
Irish white peat	MIC	49 (0.8)	221 (9.7)	646 (29.9)	294 (10.4)	c*	
	Chord _{MIN}	60 (2.5)	253 (10.5)	748 (36.6)	347 (12)	b	d**
	Br _{MIN}	70 (2.7)	296 (11.1)	854 (41.8)	397 (14.7)	a	
	Feret _{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**
	Chord _{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	
	Feret _{MAX}	108 (6.6)	627 (33.4)	1696 (78.6)	812(32.6)	a	b
	Sieving HM	106 (4.6)	567 (17.8)	1317 (19.2)	740 (11.5)		c
	Sieving DM	194 (6.3)	648 (4.8)	1796 (62.3)	939 (23)		a
Cair	MIC	55 (3.6)	238 (22.2)	846 (32.6)	362 (15.6)	c	
	Chord _{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	
	Feret _{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
	Chord _{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
	Feret _{MAX}	123 (13.8)	443 (43.6)	1850 (71.8)	857 (84.6)		a
	Sieving HM	104 (3.3)	539 (16.8)	1585 (8.7)	771 (3.6)		b
	Sieving DM	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	
	Chord _{MIN}	55 (9)	248 (28.5)	1123 (95.8)	470 (46.9)	a	
	Br _{MIN}	64 (7.4)	272 (29.3)	1215 (96.9)	515 (50)	a	
	Feret _{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
	Chord _{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
	Feret _{MAX}	88 (11.4)	446 (56.5)	2557 (177.5)	1003 (89.1)		a
	Sieving HM	222 (12.4)	1159 (46.1)	3628 (86.8)	1628 (54.8)		a
	Sieving DM	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	
	Chord _{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	
	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
	Sieving HM	105 (6.4)	501 (23.5)	2679 (188.3)	1003 (53)		a
	Sieving DM	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
	Sieving HM	157 (8)	1398 (42.5)	3936 (190.8)	1866 (64)		a
	Sieving DM	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
	Sieving HM	22 (2.7)	928 (47.6)	1784 (17.2)	975 (13.5)		a
	Sieving DM	30 (4.8)	1076 (37.4)	1857 (23.1)	1075 (19.3)		a

* Letters indicate statistically significant differences between the means of the width diameters measured by DIA, ** Letters indicate statistically significant differences between the means of the length diameters measured by DIA; *** 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.

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.



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

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 sieving DM and HM ($r = 0,99$).

DIA Length Assessment

The Pearson correlation matrix (Table 3) of the arithmetic means of the length diameters showed that all are correlated with each other ($r = 1$). Then the mean values observed for all materials are extremely close, the largest difference is 9% between the highest and lowest value, respectively Feret_{MAX} and MCC, observed on wood fiber. All averages are statistically similar; with the exception of black peat, where the maximum observed difference is 5%, or 24 μm . Among these four descriptors, Feret_{MAX} always returns a higher average value. Regarding the other indicators, size is not ranked in any particular order.

Mean Feret_{MAX} values indicate that the length of particle, 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).

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

	DIA parameters								Sieving HM	Sieving DM
	Br _{MIN}	Chord _{MIN}	Feret _{MIN}	MIC	Br _{MAX}	Chord _{MAX}	Feret _{MAX}	MCC		
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		
Sieving HM	0.46	0.27	0.46	0.02	0.77	0.76	0.76	0.76	1	
Sieving DM	0.44	0.26	0.45	0.01	0.77	0.77	0.77	0.77	0.99*	1

* Significant ($p\text{-val} < 0.01$)

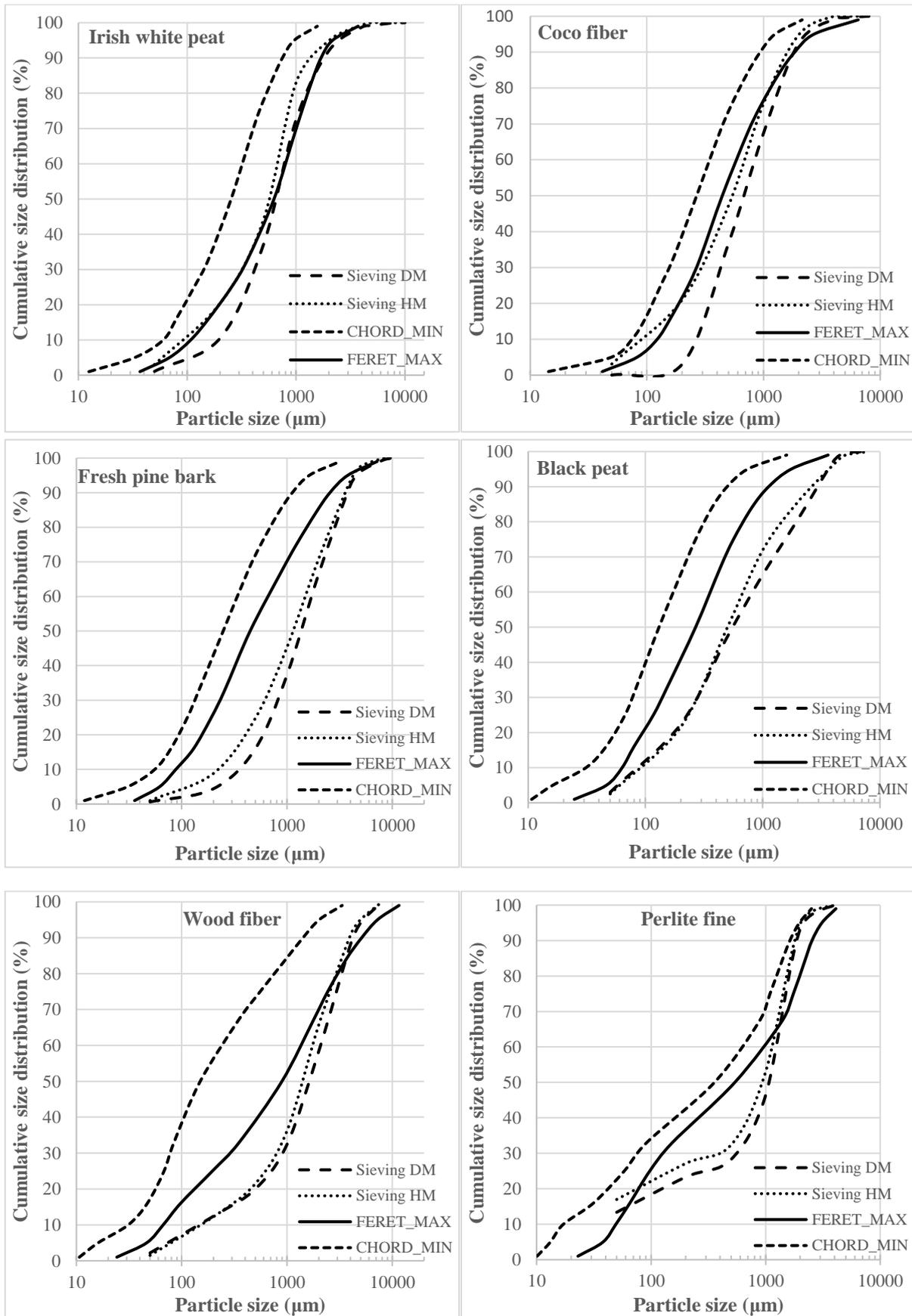


Figure 4. Cumulative particle size distribution of white peat, coir, pine bark, black peat, wood fiber and perlite measured through sieving (dry and hydrated) and dynamic image analysis.

Sieving

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

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, sieving HM showed a higher proportion of finer particles in the range from 0.5 mm to 4 mm, in comparison to sieving DM, but any difference was showed in the smaller particle size (<0.5 mm). In view of these results, it is assumed that the disaggregation for black peat from sieving HM 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 sieving DM, whereas wood fiber formed mats on the sieve surface during sieving HM, considerably limiting the dispersion of particles in water.

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

Discussion

Prior comment about sieving procedures

The number of sieves used in this study was twice that of EN 15428 standard procedure (2007), and thus gave a more detailed PSD and robust statistical analysis, as also reported by Blott & Pye (2001). The high proportion of particles smaller than 1 mm demonstrated the use of complementary sieves (50 μ m, 200 μ m, 500 μ m) in our study. Note that in the case of perlite, < 50 μ m 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.

Diameters of interest & 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 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.

As expected, by their definition (Figure 2), result have shown that all length related diameter studied give equivalent results. However, Feret_{MAX} was not expected to give the greatest values. MCC should give equal or higher values, since the diameter of the circle circumscribing the particle necessarily encompasses the distance that Feret_{MAX} measures. The hypothesis is that the calculation of the MCC is wrongly done by the software and not for Feret_{MAX}, since on several materials MCC indicates the smallest length of particles.

As Feret_{MAX} gives the greatest values it has been chosen as indicator of particle length, also knowing that it has been previously served for growing media components (Bartley, 2019; Nguyen et al., 2022). Nevertheless, it should be noted that Feret_{MAX}, as the other length descriptors, tend to underestimated particle length in case of curved particles (Figure 2).

Interest of DIA and limits

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 (Ulusoy & Igathinathane, 2016; Bartley, 2019). 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. (in press) have already fitted polynomial regressions describing strong relationships between increasing WHC and decreasing mean particle width, and even more mean particle length (considering Chord_{MIN} and Feret_{MAX}, respectively), whereas correlation was conversely very low between WHC 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.

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 & Iskander (2019) 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 by 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., 2021b), because it would induce a poor estimation of the real weight of the particles in the distribution.

Other methodological limits of QicPic

The measurement range for the QicPic device extends from 17 µm 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 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 also 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.

Discrepancies between methods

DIA and sieving

Except Feret_{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 (Chord_{MIN}, Br_{MIN}, Feret_{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 criteria that may influence these differences. Only 2-3 grams of materials are used and previously stirred in water during 10 minutes, allowing an efficient particle segregation before DIA analysis of each particle. In contrast, a much larger quantity of materials (125 ml, *i.e.*, 10 to 20 g approximately depending on the materials) is directly shaken during 7 minutes and segregated through a column of 8 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 9 classes (corresponding to the use of 8 sieves) according to cumulative undersize mass distribution, for which the proportion is affected to 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.

Sieving methods

Although results from both sieving methods are highly correlated, PSD obtained from sieving HM systematically showed smaller particles than those from sieving DM, 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.

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 ¹ (<i>i.e.</i> , 10 to 20 g)	Mass of materials per replicate: 2 to 3 g (several hundreds of thousands of particles)
Material preparation: oven dried materials at 40°C (DM) ¹ , or hydrated materials (HM)	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 ¹	Experiment duration: 2 min max (+10 min preliminary dispersion in water)
Range of measurement: 50 µm to 30 mm, depending on the sieve set (min. 4 sieves ¹); here 8 sieves used	Range of measurement: depending of the lens used; here 17 µm to 34 mm for lens M9, but limited to 20 mm in width
Particle size fractions generated	Particle individualization
Single dimensional particle characterization	Multidimensional particle characterization
Discrete values	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	Expansive cost tool
1 hour to perform 3 replicas, approximately one hour to familiarize oneself with the method and set up the measurement (choice of sieve set, stirring power). Low level of expertise required	1 hour to perform 3 replicas, several hours/days needed to set up the method and obtain a certain level of expertise
DM = standardized method (EN 15428, AFNOR 2007 for growing media)	No standard
Many scientific references based on this method	Few scientific references

1: EN 15428 standard method (AFNOR, 2007)

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 $Chord_{MIN}$ and $Feret_{MAX}$ 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 a 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.

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Paper 2: Quantitative Description and Classification of Growing Media Particle Morphology through Dynamic Image Analysis

Durand S., Jackson B.E., Fonteno W.C., Michel J.C., 2023. Quantitative Description and Classification of Growing Media Particle Morphology through Dynamic Image Analysis. *Agriculture, Special Issue Advanced Research on Soilless Culture in Horticultural Production*, 13(2), 396; <https://doi.org/10.3390/agriculture13020396>

Abstract

The physical properties of growing media are dependent on the morphological characteristics of the particles composing them. Thus, their characteristics can be more precisely altered for specific purposes by a better morphological design of materials to optimize the use of raw materials and increase water efficiency. There are many references on the relationship between basic particle size and physical properties, but the arrangement of the particles and the resulting physical properties are also affected by the shape of the particles. Growing media have seldom been characterized by shape criteria and, therefore, their influence remains unknown.

A dynamic image analyzer, the QicPic device, was used to assess particle shape and size for a wide diversity of growing media constituents. As well as Feret_{MAX} and Chord_{MIN} diameters describing individual particle length and width, respectively, individual particle shape was analyzed in terms of several descriptors (aspect ratio, circularity, roundness, and convexity).

A classification was established to discern different particle shapes and all materials were described accordingly. Correlations between particle morphology descriptors were reported, showing that the greater the particle length, the smaller the width/length ratio, circularity, roundness, and convexity. Circularity, roundness, particle length, and its associated relative span were identified as the most relevant parameters describing materials' morphology. This work shows a large diversity in particle morphology of growing media constituents, which were categorized into four classes of materials. Three classes were mainly described according to their particle shapes, with a decreasing elongation and an increasing circularity, roundness, and convexity: (1) fine and coarse wood and coir fibers; (2) all *Sphagnum* white peats, milled or sod; and (3) black peats, sedge peat, coir pith, fresh and composted pine bark, green waste compost, and perlite. A fourth class was represented by coir medium (mixing pith and fibers) and was above all characterized by high diversity in particle length. These findings extend the characterization of the materials for a more thorough evaluation of the links between particle morphology and physical properties.

Introduction

Optimizing water efficiency in container growing systems is a critical issue. This is especially important as viable water sources for agriculture are declining on a global scale, as the demand for non-mineral soil alternatives are increasing rapidly. Indeed, Blok et al. (2021) expected a quadrupling in total volume of raw materials used as growing media by 2050. The need for more knowledge of these materials has never been greater to explain their water and air retention and flow properties,

which affect irrigation strategies and, ultimately, plant growth. Research on physical properties of growing media from the 1960s to the 1980s focused on air and water contents in equilibrium, whereas dynamic approaches to flow and conductivity parameters have been pursued since the 1990s, as recently reported by Caron and Michel (2021). Examples of these endeavors are the effects of potting operations (Paquet et al., 1993; Heiskanen et al., 1996; Gruda & Schnitzler, 2004), container volume and geometry (Bilderback & Fonteno, 2004; Raviv et al., 2002; Owen & Atland, 2008), and root development in the growing media over time (Michell & Kerloch, 2019; Michel, 2019). Today, water retention curves are commonly used for assessing water and air retention properties of growing media, and, moreover, for selecting growing media constituents, particle size fractions, and the final blends by the industry.

Physical properties of growing media are dependent upon particle morphology and arrangement, as they are responsible for pore space organization and distribution. Indeed, given reasonable particle homogeneity, the larger the particle size, the higher the air-filled porosity and the lower the water retention properties (Owen & Atland, 2008; Bunt, 1983; Handreck, 1983; Caron et al., 2005; Fields et al., 2015; Nguyen et al., 2022).

In the past, particle morphology was characterized by sieving procedures. By design, sieving actually measures the second largest dimension of the particles, *i.e.*, the width. Therefore, particle “sieve size” is characterized best on particles with width/length ratios near a value of one (Bartley et al., 2022). The methodological and accuracy limits of sieving methods have led to the suggestion of the use of dynamic image analysis (DIA) to better describe particle size and shape (Bartley, 2019; Durand et al., 2021). The principle of DIA is to analyze two-dimension images of randomly orientated particles passing in a flow in front of a high-speed camera (Trubetskaya et al., 2017). Its use is particularly relevant for growing media constituents showing a large diversity of particle size and shape, with more or less elongated and granular materials. Initial studies have been recently conducted, allowing characterization of some materials and, initially, the introduction of DIA, the listing of parameters used for particle size descriptors, and the detailing of the principle and the limits depending on the devices used (Nguyen et al., 2022; Bartley, 2019; Durand et al., 2021; Durand et al., 2023). From these works, $Feret_{MAX}$ was chosen for describing particle length, where $Chord_{MIN}$ (Nguyen et al., 2022; Durand et al., 2023), or the width of the bounding rectangle, Br_{MIN} (Bartley, 2019), were selected as particle width descriptors.

In the literature, the particle shape of growing media is rarely studied, and even less its influence on physical properties. Particle shape is commonly described from the width/length ratio, and the aspect ratio or elongation, circularity, symmetry, convexity, and roundness are also noted (Blott & Pye, 2008). Studies in soil science, civil engineering, and geotechnics have shown the value of characterizing particle shape to better understand the physical and mechanical properties of the systems under study (Lim et al., 2012; Wu et al., 2021; Ulusoy, 2023). Studies carried out on mono-sized grains of sand with varying shapes showed that the greater the circularity and aspect ratio (*i.e.*, less elongated particles), the higher the bulk density and the less total porosity (Puri & Mancino, 2002; Miller & Henderson, 2011). Moreover, from sand and biochar–sand mixtures, respectively, Yi et al. (2001) and Liu et al. (2017) reported that, the more the particle roundness, the lower the total

porosity and the compressibility, due to the higher ability of those particles to fill voids than angular particles. However, for growing media, very little has been done (Bartley, 2019; Durand et al., 2021).

In view of both the lack of knowledge about particle shape and the limits to the particle size obtained from sieving, combining analysis of particle size and shape can be considered an important step to advance the understanding of particle arrangement and, then, of physical properties. From different organic materials, previous authors have shown that, the smaller the particles, the less their elongation, and the more their convexity and circularity (Nguyen et al., 2022; Gil et al., 2014; Guo et al., 2012). The same observations were reported by Durand et al. (Durand et al., 2021) on four growing media constituents (coir, pine bark, white peat, and wood fiber).

The goal of this study was to extend the description of particle morphology using the DIA process with the following objectives:

- To define shape descriptors (aspect ratio, elongation, circularity, convexity, and roundness) and the parameters used for their calculations, then to discuss their relevance for describing growing media particles with the QicPic device;
- To propose a classification adapted from Blott and Pye (2008) to describe the particle shapes of growing media constituents;
- To catalog particle shapes of materials tested according to the classification proposed;
- To analyze relationships between particle shape and size descriptors;
- To propose a first classification of growing media constituents based on their particle size and shape, and to discuss its robustness.

Materials and methods

A wide range of raw materials (22 references) representing the main growing media constituents on the current global market were selected (Schmilewski, 2017). Information about these materials is given in Table 1, and pictures of the materials are provided in Figure 1.

Table 1. Growing media components studied.

#ID	Materials	Supplier ¹ Origin		Extraction/Process	Bulk	Indicated
					Density ²	Particle Size
					g cm ⁻³	mm
#1	Coir fiber	PTH	Ivory Coast	Grounded, sieved	0.07	5–25
#2	Wood fiber (fine)	KD	Germany	Defibrated	0.08	0–2
#3	Wood fiber (medium)	KD	Germany	Defibrated	0.09	2–4
#4	Wood fiber (medium)	FLO	Germany	Defibrated	0.09	N/A
#5	White peat (fine), H5 ⁴	PTH	Ireland	Milled, screened	0.10	0–5
#6	White peat (fine), H1–H3	PTH	Canada	Milled, screened	0.11	N/A
#7	White peat (fine), H2–H6	KD	Lithuania	Milled	0.10	0–7
#8	White peat (fine), H2–H5	FLO	Latvia	Milled	0.10	0–5
#9	White peat (fine), H2–H5	FLO	Germany	Sod	0.08	0–7
#10	White peat (fine), H2–H5	KD	Lithuania	Sod	0.11	0–7
#11	White peat (medium), H2–H6	KD	Lithuania	Milled	0.11	0–25
#12	White peat (medium), H2–H5	FLO	Latvia	Milled	0.10	5–20
#13	Black peat, H6–H8	KD	Lithuania	Frozen, milled, sieved	0.17	0–5
#14	Black peat, H5–H8	FLO	Germany	Frozen	0.18	0–7
#15	Sedge peat	ETF	France	Excavated	0.24	0–10
#16	Coir pith	PTH	Sri Lanka	Grounded, sieved	0.08	0–5
#17	Fresh pine bark (fine)	PTH	France	Screened	0.22	0–5
#18	Composted pine bark (fine)	PTH	France	Screened	0.25	0–5
#19	Green waste compost	KD	Germany		0.50	0–5
#20	Perlite (fine)	KD	Germany		0.06	0.6–2.5
#21	Coir (medium)	PTH	Ivory Coast	Grounded	0.08	0–25
#22	Coir (medium)	ETB	Sri Lanka	N/A	0.05	5–25

1: ETB = EVADEA Tourbières de France, FLO = Floragard Vertiebs-GmbH, KD = Klasmann-Deilmann, PTH = Premier Tech Horticulture France. 2: Bulk density measured through EN 13041 procedure (AFNOR, 2000). 3: Particle size distribution range given by the supplier. 4: Von Post degree of humification of *Sphagnum* peat.

Dynamic Image Analysis

Dynamic image analysis (DIA) measurements were conducted with the QicPic (Sympatec GmbH, Clausthal-Zellerfeld, Germany), using a wet dispersion unit called the “Flowcell”. This DIA device and its principle were previously described by Durand et al. (2021). It allows, from hydrated materials, the analysis of particles having sizes varying between 17 µm to 33.8 mm, and shapes from 50 µm, using a high-resolution camera. However, particle roundness can accurately be determined from 500 µm.

The material to be analyzed is agitated in water with a three-armed cone-shaped agitator (VJ100 Visco Jet, Küssaberg, Germany) in a 15 L tank for 10 min to cautiously separate particles without damaging them, and then transferred from pipes (20 mm diameter) to the camera area via a peristaltic pump. Three replicates per material were carried out, with 1 to 2 g 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%, relative to the projected area density of the particles per image. Each measurement event was 2 min with a frequency of 80 digital images per second, which approximately represents 10⁷ particles per replicate. The size and shape of all particles of all images were then analyzed via the PAQXOS 4.3 software (developed by Sympatec GmbH) associated with the QicPic device. The particle distribution was weighted by projected area, corresponding to the area of the particle observed on the two-dimensional image.



Figure 1. Raw materials studied (with identification number (#ID) referenced in Table 1).

Shape Descriptors

One of the most common measurements utilizes diameters intrinsic to specific locations within each shape. The word “diameter” is usually associated with a straight line passing through the center of an object, usually a circle or sphere. In this case, a “diameter” is used more generically as a straight

line passing through a specific portion of an object. Thus, technically, an object can have several different diameters depending on what dimension of the particle is being analyzed.

Five shape descriptors were calculated and studied for this work: elongation, aspect ratio, roundness, circularity, and convexity (Figure 2). All shape descriptor values vary from 0 to 1. Figure 3 shows examples of particles to illustrate the calculation of the associated morphological descriptor values.

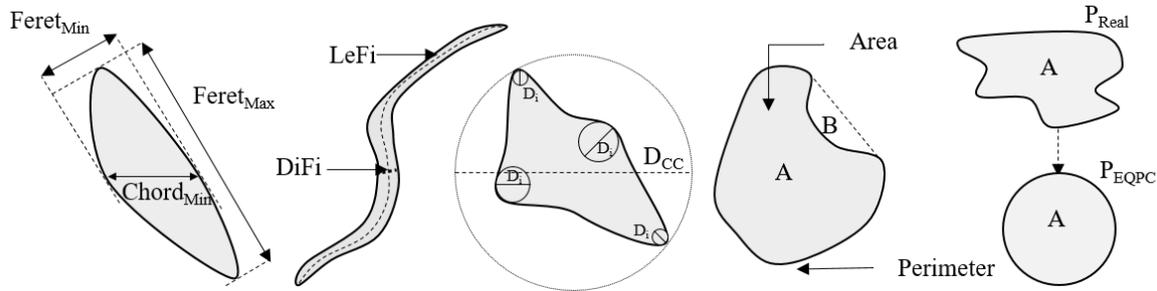


Figure 2. Schematic representation of particle size and shape assessment (Equations (1) to (5)) derived from the calculation of diameters ($Feret_{MIN}$, $Chord_{MIN}$, $Feret_{MAX}$, $DiFi$ [diameter of fiber], $LeFi$ [length of fiber], D_{CC}), area, and perimeter assessed by dynamic image analysis.



Materials	$Feret_{MAX}$	$Feret_{MIN}$	$Chord_{MIN}$	D_{CC}	D_{EQPC}	$LeFi$	$DiFi$	Aspect ratio	Circularity	Convexity	Elongation	Roundness
	μm						[0; 1]					
A - Wood fiber #3	3040	914	351	3050	550	3709	53	0.30	0.18	0.14	0.01	0.01
B - White milled peat #1	1321	617	520	1324	763	1454	277	0.47	0.65	0.77	0.19	0.23
C - Composted pine bark #18	1899	1139	1098	1901	1345	1866	762	0.60	0.83	0.95	0.41	0.35
D - Coir #22	15,603	2278	305	15,642	1884	16,910	165	0.15	0.16	0.13	0.01	0.01

Figure 3. Examples of particles of different materials (Wood fiber medium #3, Irish white peat #5, Composted pine bark 'fine' #18, and Coir #22) measured with QicPic and associated morphological descriptor values.

Aspect ratio: indicator of width/length ratio (Figure 2, Eq. 1) where width and length are respectively calculated from the minimum ($Feret_{MIN}$) and maximum ($Feret_{MAX}$) Feret diameters. Feret diameters are defined as the distance between two parallels tangents of the particle contour. Thus, $Feret_{MIN}$ is the smallest and $Feret_{MAX}$ the biggest distance among all Feret diameters of a particle.

$$Aspect\ Ratio = \frac{Feret_{MIN}}{Feret_{MAX}} \quad (Eq. 1)$$

Elongation: another indicator of width/length ratio (Figure 2, Eq. 2). The length of fiber ($LeFi$) is calculated using the skeletonization technique, and corresponds to the longest direct path from one

end to another within the particle contour. The diameter of fiber (DiFi) is calculated by dividing the projection area by the sum of all lengths of the branches of the fibre skeleton.

$$\text{Elongation} = \frac{DiFi}{LeFi} \quad (\text{Eq. 2})$$

Circularity: indicator of the deformation of the perimeter of a particle from a circle having the same area (Wadell, 1933). This shape descriptor is sometime wrongly called sphericity, but its measurement is done in two dimensions (Blott & Pye, 2008). The circularity is calculated from the particle perimeter and area. An equal projection area circle (EQPC) is calculated from the measured area of the particle, and the perimeter of the EQPC is compared to the real perimeter of the particle (Figure 2, Eq. 3). Particle circularity decreases as the perimeter increases for a given area. As discussed by Blott and Pye (2008), circularity is distinct from roundness. As an example, a square has high a circularity equal to 0.89, but a roundness equal to zero.

$$\text{Circularity} = \frac{2\sqrt{Area*\pi}}{\text{Perimeter}} \quad (\text{Eq. 3})$$

Convexity: indicator of the compactness of a particle. Convexity corresponds to the ratio of the projection area itself (A) and the area of the convex hull (A+B) (Figure 2, Eq. 4), where (B) is the open concave region of the particle. The convex hull is a surface delimited by the line of shortest distance, which connects the maximum projections on a particle outline.

$$\text{Convexity} = \frac{A}{A+B} \quad (\text{Eq. 4})$$

Roundness: indicator of the relative sharpness of the corner of a particle (Wadell, 1932). Various formulas are available to assess the roundness of the particle (Blott & Pye, 2008). Here, roundness measured by the QicPic is defined as the ratio of the average radius of curvature of all convex regions to the circumscribed circle of the particle (Figure 2, Eq. 5), in contrast with Wadell (1932), who suggested to consider the largest inscribed circle of the particle as denominator in the roundness calculation equation.

$$\text{Roundness} = \frac{\frac{\sum D_i}{n}}{D_{cc}} \quad (\text{Eq. 5})$$

with: D_i , the diameter of the i^{th} circle at the corner of the particle; n the number of corners; D_{cc} the diameter of the circumscribed circle.

Shape classification

A new classification chart, largely inspired by that defined by Blott & Pye (2008), is given in Table 2, with numerical values and illustrations for each shape descriptor. New class boundary values were calculated for circularity and roundness according to the equations used by the PAQXOS software (Eq 3, 4 and 5), differing from those used by Blott and Pye (2008) to set up their classification chart. Aspect ratio and elongation class boundaries are those proposed by Blott and Pye (2008). The class boundaries of circularity correspond to a linear progression in four classes, ranging from a square to a four-pointed star (Table 2).

Particle Size Measurement

The Chord_{MIN} diameter (Figure 2) was selected to assess the width of the particle (Nguyen et al., 2022; Trubetskaya et al., 2017; Durand et al., 2023). A chord length is defined by the maximum straight distance of two points within the particle contour. Chord_{MIN} is the shortest chord among all the maximum chords measured by the software (Figure 2). The Feret_{MAX} diameter was selected to assess the particle's length (Nguyen et al., 2022; Trubetskaya et al., 2017; Durand et al., 2023, Igathinathane et al., 2009).

Data treatment and statistical analysis

Analytics from the data measured by image analysis are provided by the software PAQXOS associated to the QicPic device. For each of size and shape descriptors mentioned above, the arithmetic mean and the values at the 10th, 50th and 90th percentiles of the cumulative distribution (D₁₀, D₅₀ and D₉₀) were determined. Also, the proportion of particles into shape classes according to Table 2, is reported. The relative span of the distribution, indicator of the distribution's width (Bartley, 2019; Bitra et al., 2009), was also calculated (Eq. 6) from the percentiles of the cumulative distribution, to highlight the diversity of size and shape within materials.

$$R_s = \frac{(D_{90} - D_{10})}{D_{50}} \quad (\text{Eq. 6})$$

with: D_{10, 50, 90}, the values of size or shape at the 10th, 50th and 90th percentile of the cumulative distribution

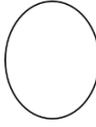
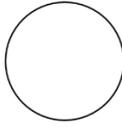
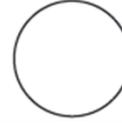
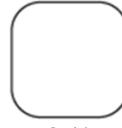
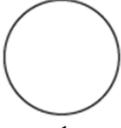
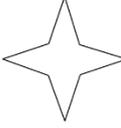
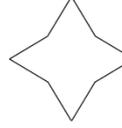
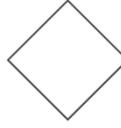
For the study of the diversity in particles as a function of particle size, the values of particle shape descriptors were averaged by particle size intervals. These intervals start from the lower value of 50 μm and are defined by a geometric progression with a ratio of 1.29.

Statistical analysis was carried out with the software R (version 4.1.1). Principal component analysis (PCA) and hierarchical cluster analysis (HCA) were conducted using the associated package Factoshiny (Vaissie et al., 2021), with the aim of distinguish similarities and differences between variables (PCA) and clusters of materials (HCA) based on particle size and shape descriptors. In addition to PCA and HCA, a Pearson correlation matrix was set up to highlight and to calculate the relationships between variables.

The statistical analysis was performed from the dataset describing the 22 materials by their particle mean size diameters (Feret_{MAX} and Chord_{MIN}), their mean shape descriptors values (aspect ratio, circularity, convexity and roundness), and the relative span (Eq. 6) of the mentioned particle size and shape descriptors.

Although the elongation variable was considered in the correlation matrix to analyze the relationships between particle size and shape descriptors, this variable was then removed for the PCA and HCA analyses. Indeed, the method of calculation makes the aspect ratio more relevant for characterizing the width/length ratio for a larger diversity of materials, whereas elongation is suitable and was calculated for fibrous particles only.

Table 2. Classification used for shape descriptors and illustrations.

Shape descriptor	Classes					
	Extremely elongated	Very elongated	Moderately elongated	Slightly elongated	Not elongated	
Aspect ratio	 0	 0.2	 0.4	 0.6	 0.8	 1
Elongation	 0	 0.2	 0.4	 0.6	 0.8	 1
Circularity	 0	 0.62	 0.83	 0.94	 0.99	 1
Roundness	 0	 0.09	 0.19	 0.41	 1	
Convexity	 0	 0.25	 0.5	 0.75	 1	

Results

Global analysis of particle shapes for the 22 growing media constituents

Among a total of 18 classes (5 classes for aspect ratio and circularity, 4 for roundness and convexity) used for describing the particle shapes, only two of them were of very low frequency for the whole of growing media constituents studied, *i.e.*, very low convexity and very high circularity, for which both mean and standard deviation values were low (Table 3). The other sixteen classes exhibited large differences in their proportions between materials, as confirmed by higher standard deviations.

Beyond the detailed description of each material, statistical analysis (PCA then HCA) were subsequently performed to analyze the relationships between morphological descriptors (all particle shape and size descriptors) and to identify the relevant parameters allowing to group materials into clusters.

Table 3. Particle shape distribution by classes, assessed from the classification proposed for shape descriptors in Table 2.

#ID	Aspect ratio					Circularity					Roundness				Convexity			
	extremely	very	moderately elongated	slightly	not	very low	low	moderate	high	very high	angular	sub-angular	sub-rounded	rounded	very low	low	moderate	high
#1	24 ²	17	23	29	8	44	32	22	2	0	48	21	22	9	9	14	15	62
#2	12	34	30	21	3	59	26	13	2	0	61	28	9	2	3	18	36	44
#3	15	32	28	22	4	58	20	19	4	0	66	26	7	2	5	19	32	44
#4	14	37	28	19	4	60	22	15	3	0	66	25	7	2	4	17	33	46
#5	2	22	37	33	7	19	52	26	3	0	26	32	32	9	0	2	16	82
#6	2	20	35	36	7	18	46	33	4	0	36	34	22	8	0	2	16	82
#7	2	18	33	39	8	17	44	36	4	0	36	40	19	6	0	2	16	82
#8	2	19	35	35	8	26	47	24	3	0	31	34	26	9	0	3	21	76
#9	6	26	33	29	6	28	43	27	3	0	44	32	18	6	1	5	19	74
#10	1	15	31	43	10	15	39	41	5	0	35	42	17	6	0	2	15	83
#11	2	18	34	39	8	17	43	35	4	0	35	40	19	6	0	2	16	82
#12	5	19	33	35	9	35	35	25	6	0	35	38	21	5	2	5	24	70
#13	1	12	30	46	11	11	37	46	7	0	29	36	24	11	0	2	11	87
#14	1	10	28	47	14	10	37	48	5	0	22	28	29	21	0	2	9	89
#15	0	3	29	55	12	2	17	67	13	0	17	45	25	13	0	0	4	96
#16	1	4	26	52	16	4	42	51	3	0	16	23	37	25	1	1	3	96
#17	1	12	30	45	12	8	45	43	4	0	18	32	34	16	0	0	5	95
#18	1	9	28	49	14	4	36	53	7	0	17	36	31	16	0	0	3	97
#19	1	6	24	53	16	7	22	61	10	0	23	38	24	16	0	2	5	93
#20	0	2	27	55	16	1	41	52	6	0	6	26	48	20	0	0	3	97
#21	12	8	22	45	13	20	27	50	4	0	40	27	19	14	4	6	8	82
#22	4	8	26	49	13	12	29	53	6	0	30	29	25	16	4	3	5	87
Mean	5.0	16.0	29.5	39.8	10.0	21.6	35.5	38.2	4.9	0.0	33.5	32.4	23.4	10.8	1.5	4.9	14.3	79.4
SD ¹	6.4	9.9	4.1	11.0	4.0	18.5	9.9	15.4	2.6	0.0	16.1	6.5	9.7	6.5	2.4	6.1	10.1	16.8

1: SD = standard deviation. 2: Standard deviation for each shape class measured on three replicates never exceeds 5%.

Correlations between morphological descriptors & identification of relevant parameters

PCA correlation circle, performed from arithmetic mean of the size and shape descriptors and their associated relative span determined for the 22 materials, is presented Figure 4.

The first component of the PCA is mainly based on particle shape descriptors and their associated relative span, with the sole exception of span roundness. This component explained 66% of the total variance (Figure 4). Those significantly ($p\text{-val} < 0.01$) contributing the most ($r > |0.95|$) to the first component of the PCA were mean and span circularity, mean and span convexity, and span aspect ratio. The second component, built by the mean and span length and span roundness, only explained 14% of the variability.

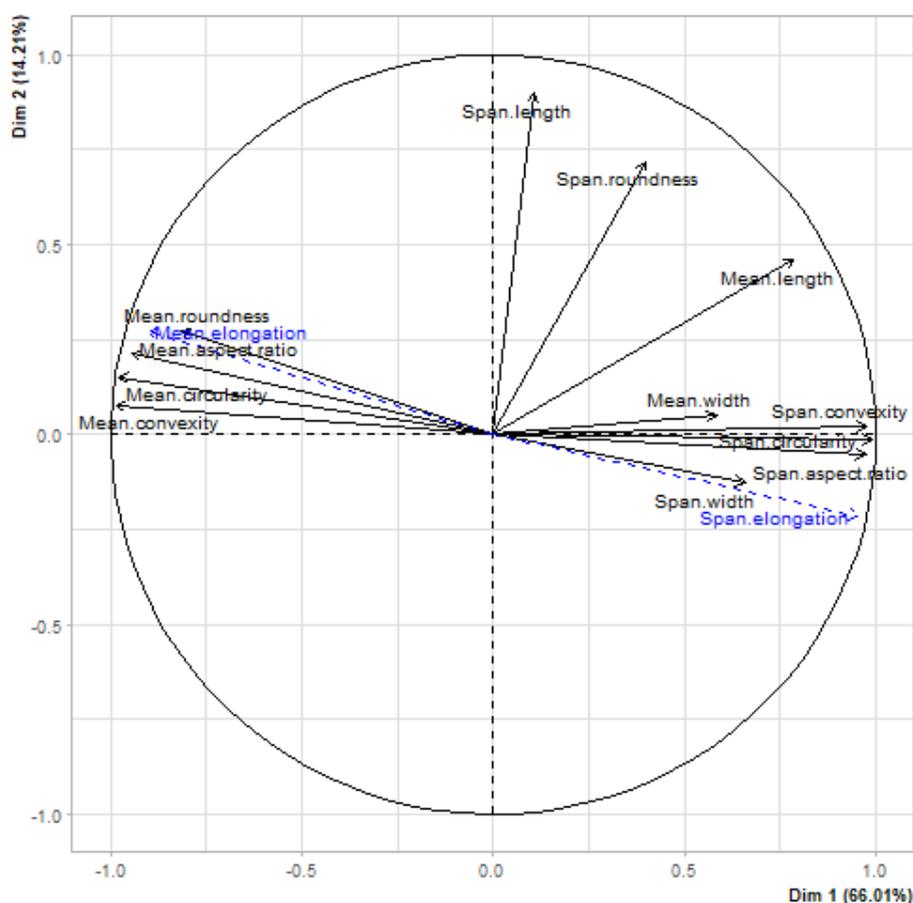


Figure 4. PCA correlation circle for variables describing particle size, shape, and diversity.

Pearson correlation matrix (Table 4) also highlighted significant correlations between shape descriptors (p -value < 0.001), with higher correlations ($r > 0.92$) between elongation, aspect ratio, circularity and convexity, whereas roundness showed the least correlation with the other shape descriptors. Particle length and width were also significantly correlated ($r = 0.75$). Weaker but significant correlations were found between particle size (considering both length and width) and elongation, circularity and convexity, but not for roundness. Also, particle length was more correlated with shape descriptors than particle width. To sum up, the higher the particle length, the lower the width/length ratio (more elongated particles), the circularity and the convexity.

Table 4. Correlation matrix between arithmetic means of particle shape and size descriptors for the 22 growing media constituents studied.

	Elongation	Aspect ratio	Roundness	Circularity	Convexity	Width	Length
Elongation	1						
Aspect ratio	0.95 ***	1					
Roundness	0.77 ***	0.88 ***	1				
Circularity	0.97 ***	0.97 ***	0.82 ***	1			
Convexity	0.92 ***	0.96 ***	0.86 ***	0.98 ***	1		
Width	-0.56 **	-0.42	-0.14	-0.57 **	-0.48 *	1	
Length	-0.60 **	-0.60 **	-0.36	-0.70 ***	-0.70 ***	0.75 ***	1

Significance of the linear correlation, *** p -value < 0.001, ** p -value < 0.01, * p -value < 0.05.

Hierarchical Clustering Analysis (HCA) of growing media constituents

The HCA, performed from the two first components obtained from the PCA, allowed to identify four clusters of materials (Figure 5), for which mean and relative span of shape and size descriptors were presented in Table 5.

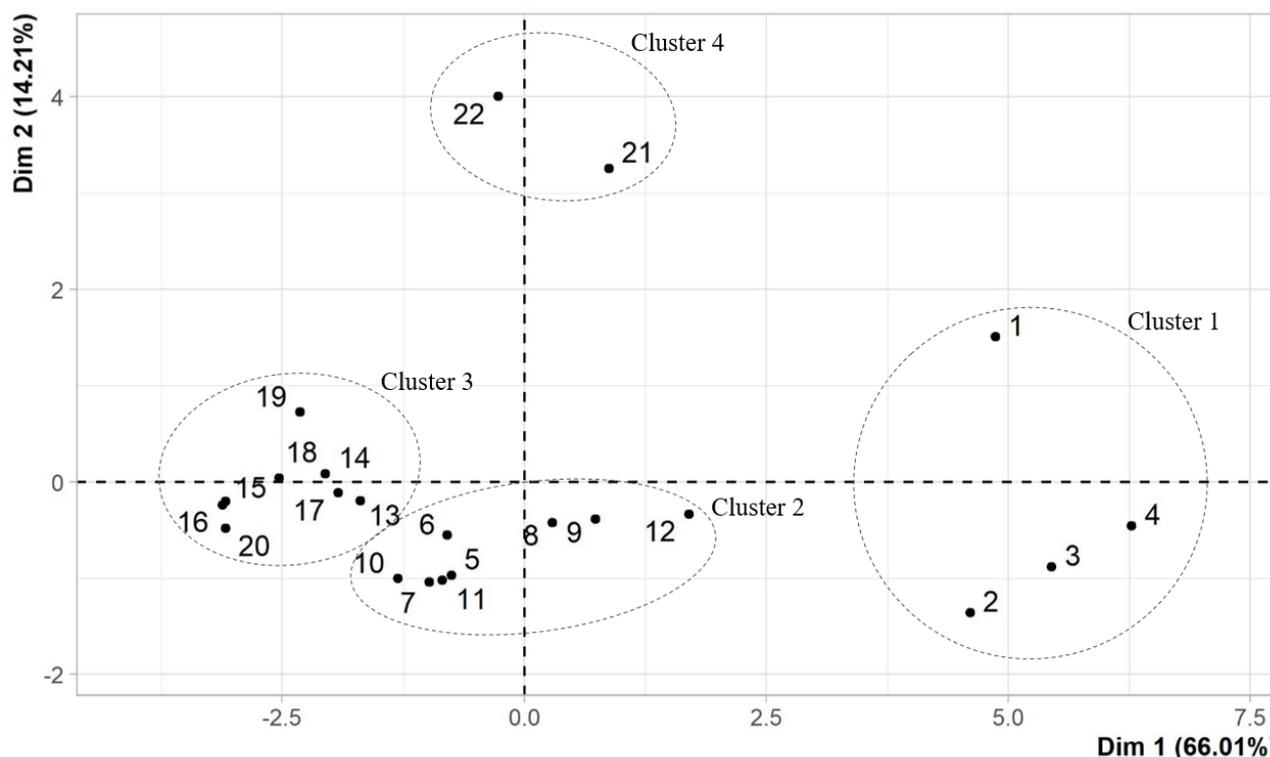


Figure 5. Identification of four clusters by HCA obtained from the PCA individuals (numbers correspond to the ID number given for all growing media constituents listed in Table 1).

In details, clusters 1, 2 and 3 were only differentiated by the first PCA component, and then were mainly classified in ascending order according to the mean values of shape descriptors and in descending order according to their relative span, rather than the particle length. Although the cluster 4 was quite close to cluster 2 on the basis of the mean values of shape descriptors (main PCA component), this cluster 4 differed from the others due to the diversity (relative span) in roundness and by the particle length (2nd PCA dimension, Figure 4).

The first cluster regrouped fine (#2) and medium wood fibers (#3 and #4) and coir fiber (#1), and was defined by the lower mean values for aspect ratio (0.42 to 0.46), circularity (0.57 to 0.60), convexity (0.67 to 0.71), and roundness (0.09 to 0.16), *i.e.*, by more elongated and angular, and less circular and convex particle shapes (Table 5). Indeed, these materials were particularly characterized by high contents in the most elongated particles (41% to 51% for the sum of extremely and very elongated particles), angular particles (48% to 66% of angular particles), the less circular particles (44% to 60% of very low circular particles), and by the less proportions in highly convex particles (44% to 62%) compared to the other clusters (Table 3). This first cluster also showed the highest relative span for the aspect ratio, circularity, and convexity, indicating a higher diversity in particle shapes for these materials (Table 5).

Table 5. Mean and relative span of shape and size descriptors for the 22 tested materials, and identification of clusters from hierarchical cluster analysis.

Cluster #ID ¹ Material	Aspect Ratio	Circularity	Convexity	Roundness	Width (mm)	Length (mm)
	Mean [Relative Span]					
#1 Coir fiber	0.46 ² [1.3]	0.60 [0.9]	0.71 [0.8]	0.16 [3.8]	0.62 ³ [3.8]	3.85 [5.2]
#2 Wood fiber (fine)	0.43 [1.3]	0.57 [1.1]	0.68 [0.7]	0.10 [2.4]	0.48 [5.8]	1.71 [4.3]
#3 Wood fiber (medium)	0.44 [1.3]	0.58 [1.1]	0.67 [0.9]	0.09 [2.8]	0.47 [9.2]	1.86 [5.6]
1 #4 Wood fiber (medium)	0.42 [1.3]	0.57 [1.1]	0.68 [0.7]	0.09 [2.7]	0.82 [10.3]	2.96 [7.3]
Cluster 1 value range	0.42–0.46 [1.3]	0.57–0.60 [0.9–1.1]	0.67–0.71 [0.7–0.9]	0.09–0.16 [2.4–3.8]	0.47–0.82 [3.8–10.3]	1.71–3.85 [4.3–7.3]
#5 White peat, H5	0.54 [0.8]	0.74 [0.5]	0.83 [0.3]	0.20 [2.2]	0.35 [2.7]	0.81 [2.5]
#6 White peat, H1–H3	0.55 [0.8]	0.76 [0.5]	0.83 [0.3]	0.17 [2.7]	0.23 [2.6]	0.60 [3.0]
#7 White peat (fine), H2–H6	0.57 [0.8]	0.76 [0.5]	0.82 [0.3]	0.15 [2.3]	0.20 [2.4]	0.52 [3.1]
#8 White peat (fine), H2–H5	0.55 [0.9]	0.71 [0.5]	0.81 [0.3]	0.18 [2.5]	0.48 [4.2]	1.21 [4.9]
#9 White peat (fine), H2–H5	0.50 [1.0]	0.71 [0.6]	0.79 [0.4]	0.15 [3.0]	0.25 [2.9]	0.82 [4.2]
2 #10 White peat (fine), H2–H5	0.59 [0.8]	0.78 [0.4]	0.83 [0.3]	0.15 [2.2]	0.20 [2.7]	0.49 [3.6]
#11 White peat (medium), H2–H6	0.56 [0.8]	0.76 [0.5]	0.82 [0.3]	0.15 [2.3]	0.23 [2.7]	0.56 [3.4]
#12 White peat (medium), H2–H5	0.55 [0.9]	0.69 [0.7]	0.78 [0.4]	0.16 [2.2]	0.68 [6.4]	1.89 [7.1]
Cluster 2 value range	0.50–0.59 [0.8–1.0]	0.69–0.78 [0.4–0.7]	0.78–0.83 [0.3–0.4]	0.15–0.20 [2.2–3.0]	0.20–0.68 [2.6–6.4]	0.49–1.89 [2.5–7.1]
#13 Black peat, H6–H8	0.61 [0.7]	0.80 [0.4]	0.85 [0.2]	0.19 [2.8]	0.23 [3.6]	0.49 [4.0]
#14 Black peat, H5–H8	0.62 [0.7]	0.80 [0.4]	0.86 [0.2]	0.25 [2.7]	0.33 [3.6]	0.64 [3.9]
#15 Sedge peat	0.64 [0.5]	0.87 [0.2]	0.90 [0.2]	0.21 [2.5]	0.12 [4.8]	0.23 [5.3]
#16 Coir pith	0.65 [0.6]	0.82 [0.2]	0.88 [0.1]	0.29 [2.0]	0.41 [3.2]	0.86 [3.9]
#17 Fresh pine bark (fine)	0.61 [0.7]	0.80 [0.3]	0.88 [0.2]	0.24 [2.3]	0.47 [4.3]	1.00 [5.5]
3 #18 Composted pine bark (fine)	0.63 [0.6]	0.83 [0.3]	0.88 [0.2]	0.24 [2.4]	0.33 [4.2]	0.70 [5.6]
#19 Green waste compost	0.65 [0.6]	0.84 [0.3]	0.87 [0.2]	0.22 [3.1]	0.28 [4.3]	0.79 [5.9]
#20 Perlite (fine)	0.67 [0.5]	0.84 [0.2]	0.91 [0.2]	0.29 [1.6]	0.63 [4.5]	1.00 [4.6]
Cluster 3 value range	0.61–0.67 [0.5–0.7]	0.80–0.87 [0.2–0.4]	0.85–0.91 [0.1–0.2]	0.19–0.29 [1.6–3.1]	0.12–0.63 [3.2–4.8]	0.23–1.00 [3.9–5.9]
#21 Coir (medium)	0.58 [1.0]	0.75 [0.7]	0.80 [0.5]	0.19 [3.9]	0.28 [2.6]	1.81 [19.6]
#22 Coir (medium)	0.61 [0.7]	0.79 [0.5]	0.83 [0.3]	0.22 [3.3]	0.43 [4.5]	2.47 [27.1]
4 Cluster 4 value range	0.58–0.61 [0.7–1.0]	0.75–0.79 [0.5–0.7]	0.80–0.83 [0.3–0.5]	0.19–0.22 [3.3–3.9]	0.28–0.43 [2.6–4.5]	1.81–2.47 [19.6–27.1]

1: Identification number defined in Table 1.

2: Standard deviation of the mean of the shape descriptors measured on the three repetitions never exceeds 0.03.

3: Standard deviation of the mean width and length measured over three replicates varies from several tens to several hundred microns.

The second cluster regrouped all white peats, regardless of their geographical origins, particle sizes, and extraction processes (*i.e.*, fine and medium, milled and sod (#5 to #12)), with intermediate mean values for aspect ratio (0.50 to 0.59), circularity (0.69 to 0.78), convexity (0.78 to 0.83), and roundness (0.15 to 0.20) (Table 5). The materials comprising this cluster were characterized by slightly to very elongated particles (86% to 91%, *i.e.*, very low contents in extremely elongated and not-elongated particles), particles having moderately to very low circularity (94% to 97%), angular to sub-rounded particles (91% to 95%), and mainly highly convex particles (70% to 82%) (Table 3).

The third cluster was composed of black peats (#13 and #14), sedge peat (#15), coir fine (#16), fresh (#17) and composted (#18) pine bark, green waste compost (#19), and fine perlite (#20). This cluster was defined by higher mean values for aspect ratio (0.60 to 0.67), circularity (0.80 to 0.87), convexity (0.85 to 0.91), and roundness (0.19 to 0.29), *i.e.*, by both less elongated and angular, and more circular and convex, particle shapes (Table 5). These materials were characterized by almost all having a very convex particle shape (>87%), and by the lowest proportions of very to extremely elongated particles (2 to 13%), particles having very low circularity (1 to 11%), and angular particles (6 to 29%) (Table 3). The relative spans of the materials comprising this cluster were also the lowest, indicating more homogeneous shapes (Table 5).

The fourth cluster was only composed of two raw materials: coir medium (#21 and #22). The mean values for aspect ratio (0.58 to 0.61), circularity (0.75 to 0.79), convexity (0.80 to 0.83), and roundness (0.19 to 0.22) were similar or very close to those that were highest for cluster 2 and lowest for cluster 3. However, in contrast with the other clusters, these materials were also characterized by very high relative spans in particle length, and, to a lesser extent, in particle roundness (Table 5). These large diversities in particle length and roundness observed for the coir medium seem to confirm the distinction of particle morphologies within this material. Indeed, its results from a mixture between coir pith (small size, slightly elongated, moderately circular, and highly convex particles) and coir fibers (large size, very or extremely elongated, slightly circular, and slightly convex particles), represented by samples #16 and #1 in clusters 3 and 1, respectively.

Shape diversity as a function of particle length

Mean values of the shape descriptors (aspect ratio, circularity, convexity, and roundness) are plotted (Figure 6) as a function of the particle length (expressed by $Feret_{MAX}$) for the paragon of each cluster (Table 5): wood fiber medium (#3, Figure 6a), Irish white peat (#5, Figure 6b), composted pine bark fine (#18, Figure 6c), and coir medium (#22, Figure 6d).

Overall, decreases in values of shape descriptors and, thus, changes in shapes were observed according to an increasing particle length (Figure 6), except only roundness for wood fiber (cluster 1). Thus, the longer the particle, the more their width/length ratio (*i.e.*, the less the aspect ratio), and the less their circularity, convexity, and roundness.

Regardless of the magnitude of the decreases in the values of the shape descriptors observed, most important changes (*i.e.*, diversity) in particle shape were observed for the finest fractions, for all materials (< 1 to 1.5 mm for wood fiber medium, Irish white peat, and composted pine bark, and < 2.5 mm for coir medium, approximately), but, in particular, for wood fiber medium and coir medium. For the longest particle size, changes in shape descriptors were quite low for wood fiber medium (cluster 1) and coir medium (cluster 4), suggesting a similar particle shape. Conversely, values in shape descriptors very slowly but continuously decreased for increasing particle length of Irish white peat (cluster 2) and composted pine bark (cluster 3). Thus, the magnitude and the evolution of decreases in shape descriptors according to particle length differed, depending on the cluster. The lower the magnitude, the higher the homogeneity in particle shapes (observed in Figure 6, and measured, through the relative spans of shape descriptors, in Table 5). Consequently, composted pine

bark (cluster 3) can be described as the most homogenous material in terms of particle shape, in contrast with the other clusters, where higher diversity in shapes according to the particle size were observed. For clusters 1 and 4, high diversity in particle shape only concerned the finest < 1.5 and 2.5mm fractions, respectively, whereas similar shapes were observed for higher particle sizes. In contrast, the decrease (*i.e.*, the changes) in shapes for cluster 2 was continuously observed according to the increasing particle length.

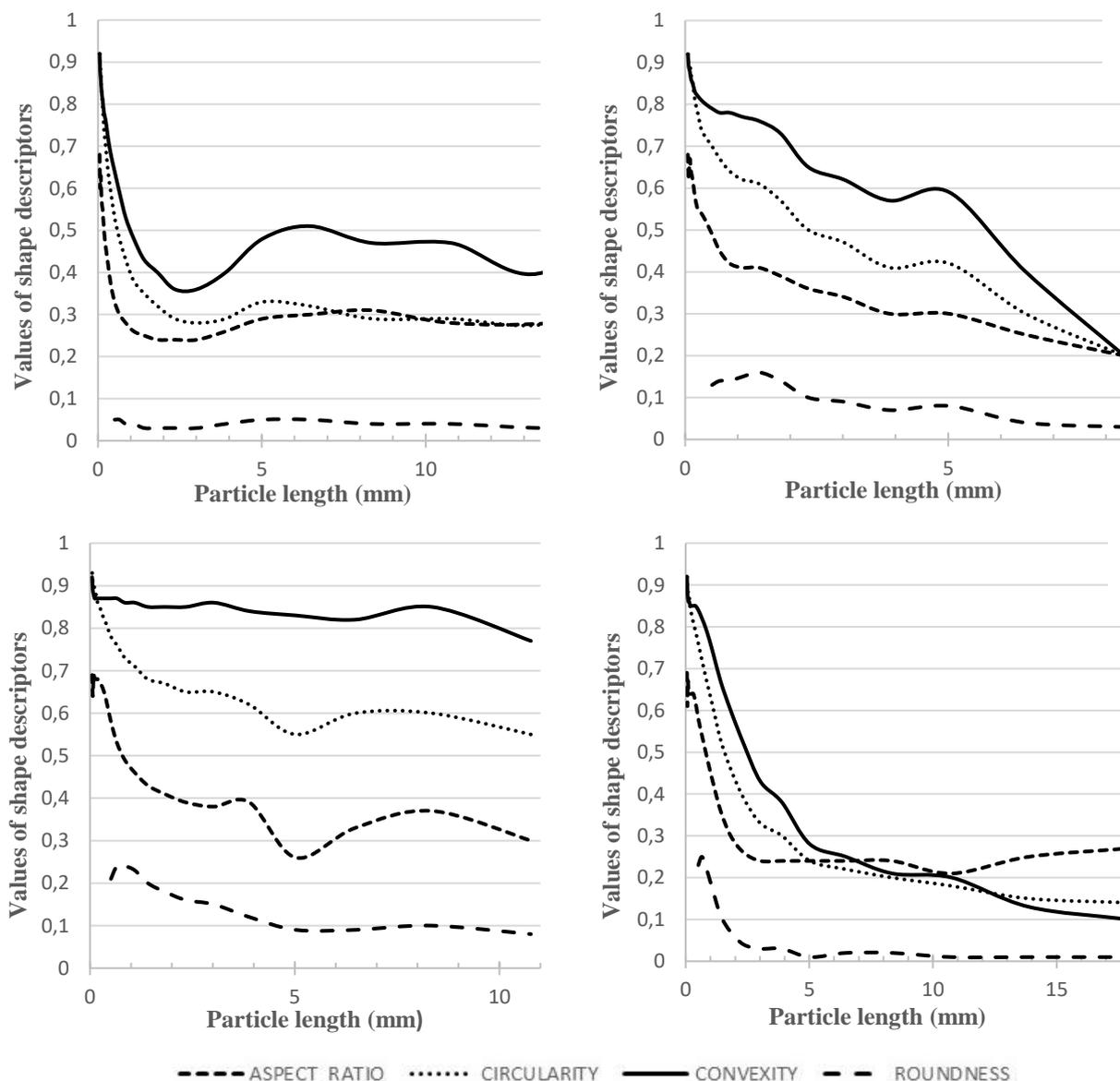


Figure 6. Particle shapes according to their length ($Feret_{MAX}$, in mm) for (a) Wood fiber medium #3, (b) Irish white peat #5, (c) Composted pine bark 'fine' #18, and (d) Coir #22.

Discussion

Relevance of shape descriptors for characterizing growing media constituents

In addition to diameters describing particle size (Figure 2), five shape descriptors were studied in order to analyze particle shapes of growing media constituents as precisely and accurately as possible, and then to define the most relevant descriptors to be considered. Although multiple correlations were

found between shape descriptors (Figure 4, Table 4), some limits and constraints should be considered regarding the relevance of using one or another shape descriptor to avoid misinterpretations in the particle shape analysis. Points for discussion are as follows:

Both aspect ratio (Equation (1)) and elongation (Equation (2)) describe the width/length ratio. However, elongation calculated from Equation (2) assumes that the particle width is equal to its surface divided by its length, which is only true for elongated-rectangular shaped particles (*e.g.*, fibers). For non-elongated particles, the particle length (Le_{Fi}) is overestimated, and consequently, the width/length ratio underestimated. In contrast, the aspect ratio is most appropriate for non-curved particles. Indeed, for curved particles, $Feret_{MIN}$ overestimates the particle width, and $Feret_{MAX}$ minimizes its length, resulting in an overestimation of the width/length ratio.

Convexity is a relevant shape descriptor for non-curved particles, where concave areas are clearly defined (*cf.* area B on Figure 2). Indeed, for curved particles such as fibers, concave regions correspond to the inner area between the extremities of curved particles, thus resulting in underestimating the convexity.

Although circularity is not based on particle length and width, but on particle area and perimeter, it is highly related to the width/length ratio of particles. The perimeter of a particle increases while its width/length ratio decreases for a given area. Moreover, circularity is also related to the convexity of a particle. Indeed, the more a particle has concavities, the more its perimeter increases compared to its area, which is reflected by the circularity. In contrast with previously mentioned shape descriptors, circularity is then adapted for all particle shapes, and could be considered as a strong indicator to differentiate materials.

Roundness calculation also considers particle length, but is not influenced by the width/length ratio of particles, in terms of either its perimeter or area, nor its curvature. As observed, this shape descriptor was the less correlated with the others.

From these previous comments, circularity and roundness could be considered as the most relevant shape descriptors for the encountered diversity of growing media particle shapes.

Mean values and relative spans of shape descriptors were calculated according to the literature (Blott & Pye, 2001; Bartley, 2019; Bitra et al., 2009) to compare our materials. However, both values do not accurately describe particle shape distribution. An adapted shape classification previously given by the chart of Blott and Pye (2008) was used to better reflect the particle distribution (Table 3).

Relevance of growing media classification according to particle size and shape

In addition to high correlations observed and already discussed between particle shape descriptors, relationships between particle shape and size descriptors were also shown. In general, the greater the particle length, the less the width/length ratio, circularity, convexity, and roundness. This interpretation, obtained from a large diversity of growing media constituents, agreed those already reported by Gil et al. (2014) on milled poplar and corn stover, and by Guo et al. (2012) on ground pine, beanstalk, rice straw, and reed.

Four clusters were defined from hierarchical cluster analysis. The first three of these (clusters 1, 2, 3) were mainly discriminated by their particle shapes rather than their sizes, as observed in the PCA correlation circle (Figure 4). The fourth was separated from the others by its particle length (mean length and, even more, span length) and its span roundness, due to the heterogeneity of these materials (coir medium) resulting from a mix of coir pith and fibers.

This classification is the first to consider both particle size and length. However, its robustness should be viewed with caution, although it was built from a large and diverse panel of 22 raw materials used as growing media constituents. Its main limit is a technical one, and based on the maximum particle width of <20 mm that can be analyzed by the QicPic device. Thus, coarser materials such as some coarse barks, sod peats, and coir chips cannot be analyzed and, thus, cannot be considered in such classification. It is likely that coarser particles would influence the HCA and then the definition of clusters, with a higher weight of particle size in comparison with particle shape. However, since most of growing media constituents do not exceed 20 mm, this classification into 4 clusters remains relevant.

Two-dimensional analysis

Comparing the particle size distribution obtained by sieving and image analysis has already shown that a projected area-weighted distribution places more importance on small particles than larger ones, in contrast to the mass-weighting used in sieving (Bartley, 2019; Li & Iskander, 2020; Durand et al., 2023). Volume weighting is possible using some DIA tools (including QicPic) and it would be preferable to have a better comparison with sieving. However, the transition from two-dimensional images to a three-dimensional modeled object implies a loss of information quality. Indeed, the image analysis tools require a parameterization that consists of choosing a single volume model (sphere, ellipse, or cylinder) for the whole measurement. However, as shown in this paper, the particles of a material are very diversified and do not necessarily have a morphology adapted to the volume models proposed. Therefore, the three-dimensional modeling of particles would induce a poor estimation of the real weight of the particles in the distribution. Although two dimensions do not reflect the complete shape of the particle, this way of representing a sample allows more accuracy.

Conclusions

From four shape descriptors (aspect ratio, circularity, roundness, and convexity) and the introduction of an adapted classification used to describe them, the diversity in particle shape for a wide panel of growing media constituents was detailed through the use of DIA.

High correlations were found between particle shapes, and between particle shape and length, and with particle length, so that the greater the particle length, the lower the values of width/length ratio, circularity, roundness, and convexity. Overall, circularity, roundness, particle length, and particle span (*i.e.*, particle length diversity) seemed to provide the most useful variables to describe particle morphology.

Moreover, four types of growing media constituents were defined from hierarchical cluster analysis, combining particle shape and size. The first three of these were mainly arranged according to the increasing mean values of all shape descriptors (*i.e.*, less and less elongated, as well as more and more circular, round, and convex particles) as follows:

- Fine and coarse wood and coir fibers;
- *Sphagnum* white peats, regardless of their particle sizes (fine and medium) and extraction processes (milled and sod);
- Black peats, sedge peat, coir fine, fresh and composted pine bark, green waste compost, and fine perlite.

The coir medium representing cluster 4 was characterized by a particle shape similar to that of clusters 2 and 3, but more specifically by very high diversity in particle length, resulting from a mixture between coir pith and fibers.

Through the use of DIA, this work made an improvement to the qualification and quantification of particle morphology not previously reported for growing media constituents. This knowledge provides a more extensive characterization of the materials, which will enable a more refined evaluation of the relationship between particle morphology and physical properties. As relevant relationships will be discovered, growing media manufacturers will have better information to design the raw materials and blends.

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Sum up of the part I:

This first part allowed to present and parameterize the dynamic image analysis method and to highlight the differences with the standard sieving method. Then, the different morphological indicators were studied and evaluated in order to select the most relevant ones to characterize the morphology (circularity and length) and the associated morphological diversity (length relative span) of all the materials studied. Finally, a classification based on the morphological indicators of the materials was proposed; highlighting three groups of material, and a fourth one discriminated by its diversity of particle size.

Having studied the morphology of the particles in detail, the rest of this work will focus on the links between morphology and physical properties of the materials.

Part II: Relationships between particle morphology and physical properties

Lists of materials studied (material pictures in General Introduction, Figure 12)

Paper 3

4. Fresh pine bark 'fine'
8. German black peat
9. Coir (Ivory Coast)
23. Lithuanian white milled peat 'medium'
29. Wood fiber 'medium' (Greenfibre)

Paper 4

1. Composted pine bark 'fine'
4. Fresh pine bark 'fine'
7. Baltic black peat
8. German black peat
9. Coir (Ivory Coast)
12. Coir pith
13. Green waste compost
14. Sedge peat
15. Perlite 'fine'
16. Perlite 'coarse'
19. Irish white milled peat
20. Latvian white milled peat 'fine'
22. Lithuanian white milled peat
23. Lithuanian white milled peat 'medium'
24. Lithuanian white sod peat
25. German white sod peat 'fine'
28. Wood fiber 'fine' (Greenfibre)
29. Wood fiber 'medium' (Greenfibre)
30. Wood fiber 'fine' (Florafibre)

Paper 5

4. Fresh pine bark 'fine'
8. German black peat
9. Coir (Ivory Coast)
23. Lithuanian white milled peat 'medium'
29. Wood fiber 'medium' (Greenfibre)

Paper 3: Solid phase organization and shrinkage properties of some growing media constituents according to particle size

Durand, S., Boivin, P., Fonteno, W.C., Michel J.C., submitted soon to *Soil Science Society of America Journal*

Abstract

Mainly designed from their particle size to provide the most suitable root environment in terms of water retention properties and ability to drain, relationships between particle size of growing media constituents and physical properties are not well explained, which requires to go forward in the knowledge of particle arrangement (*i.e.*, structure) and shrinkage properties.

This paper aimed then to finely analyze shrinkage curves as function of particle morphology (size and shape) for some main growing media constituents (white and black peats, coir, pine bark and wood fiber) and particle size fractions obtained by sieving from these raw materials. For that, Hyprop systems coupled to linear vertical displacement transducers, and the QicPic device were used to establish shrinkage curves and to assess particle size and shape, respectively. Relationships between particle arrangement and particle morphology were studied in terms of the plasma and structural components of the total porosity on the one hand, and of the mean particle length and circularity for the other hand.

Volumes and proportions of plasma and structural porosity vary according to the nature of the material. However, differences in total porosity observed for particle size fractions derived from a same raw material only resulted of changes in structural porosity, whatever the materials. This latter represents the major part of the total porosity, and seems to depend on both particle size and circularity, which however vary in opposite ways. The resulting of an increase in particle size coupled to a decrease in circularity led to higher structural porosity in intermediate particle size fractions for black and white peats, and wood fiber. Unlike bark and coir where this volume increases with increasing particles size fraction and the decreasing circularity.

The ability to shrink also depends on the nature of growing media constituents, which can be globally ranged in descending order as follows: peat > coir > pine bark > wood fiber. Structural shrinkage mainly concerns the finest particle size fractions of materials (mean particle length < 0.5 mm), except for white peat for which a larger range in particle length is concerned. Indeed, drying process led to a structural shrinkage close to saturation for finer particle size fractions only, whereas a plasma shrinkage was observed for all particle size fractions.

This work revealed that particle arrangement and physical behaviors during drying of materials depend on the nature of constituents, but also highly on particle size (more exactly, particle length).

Introduction

As for soils, water retention and drainage functions of growing media result from particle arrangement which in part depend on particle size distribution. However, other parameters affect their

particle arrangement (Caron & Michel, 2021). Mixing (Pokorny et al., 1986) and potting operations (Gruda & Schnitzler, 2004) may greatly modify the bulk density (Milks et al., 1989) before use. During cultivation, changes in water content related to the irrigation management (Fonteno et al., 1981; Heiskanen et al., 1996; Gruda & Schnitzler, 2004; Qi et al., 2011; Michel & Kerloch, 2017), root development (Michel & Kerloch, 2017; Michel, 2019) also contribute to modify solid and pore space organization, and then water and air availability for the plants. Shrinkage can also result from biodegradation of some growing media components (Caron & Michel, 2021). The structure does not "come in the bag", but is created during use (Drzal et al., 1999). Particle arrangement is thus complex, fragile and spatially heterogeneous (Caron et al., 2015; Fonteno, 1996).

Even if the consequences of particle reorganization are mainly assessed through the changes in water and air contents or flows, shrinkage properties of growing media are in contrast little investigated. Otherwise, they are most of the time determined by a static approach, as reported by Cattivello et al. (1997), Michel et al. (2001, 2004) on peat samples. To date, only Qi et al. (2011) investigated the dynamic of shrinkage (and also swelling) for a *Sphagnum* white peat during several drying/wetting cycles, and reported two phases of shrinkage with both irreversible changes in volume and hysteresis phenomena after a first drying/wetting cycle.

Regarding soil functional properties (Gerke & van Genuchten, 1993; Boivin et al., 2004) the pore space is usually partitioned into micro- and macroporosity, describing intra- and interaggregate pores, respectively (Schäffer et al., 2013; Zhou et al., 2017). Microporosity also refers to plasma porosity or matrix porosity coming from smaller soil particles (silt and clay) creating pores with < 10 to 15 μm diameters (Fiès & Bruand, 1998) which mainly govern water storage. Conversely, macroporosity refers to structural or interpedal (*i.e.*, inter-aggregate) porosity, with higher pore size diameters favoring drainage and aeration. Both porosities are able to shrink or swell during drying or wetting (Braudeau et al., 2004).

Pore space of growing media is also usually partitioned in micro- and macroporosity for the same respective water storage and drainage functions, but the terms of plasma or matrix, as well as those of structural or interpedal porosities are not used. Because most of growing media mainly consist of coarser particles than those of soils (Bartley, 2019; Durand et al., 2023a) and also are non-colloidal particles (except black peats), particle arrangement does not really allow the creation of aggregates and cracks. Thus, the correspondence between micro- and macroporosity with intra- and interaggregate pores cannot be relevant. Pore size diameters defining micro- and macroporosity in growing media also largely differs than those defined for soils: air-filled porosity is defined at -1 kPa (AFNOR, 2000) corresponding to > 300 μm pore diameters, whereas microporosity refers to smaller pores, in which available water for plants is released between -1 and -10 kPa corresponding to pore diameters from 30 to 300 μm (De Boodt & Verdonck, 1972; Caron & Michel, 2021). However, these designations are somewhat arbitrary (Drzal et al., 1999), since pore have different functions depending on its location in a container and the geometry of the container (Bilderback & Fonteno, 1987). As for soils, shrinkage both micro- and macroporosity have been reported for some growing media by Michel et al. (2001) and Qi et al. (2011).

Soil shrinkage has been studied for a long time to quantify hydro-structural behavior (Haines, 1923; Tempany, 1917), *via* shrinkage curve which describes the change in the specific bulk volume (per unit of dry mass) as a function of water content during a drying process (Braudeau, 1987; Braudeau & Bruand, 1993). Several approaches have been developed to model shrinkage curves (Giráldez et al., 1983; MacGarry & Malafant, 1987; Tariq & Durnford, 1993; Braudeau et al., 2004; Peng & Horn, 2005; Chertkov, 2007a, 2007b, 2008, 2012), suggesting to partition the curves in two to five domains for assessing the hydrostructural stability with respect to soil functional properties, *i.e.* water storage and drainage (Schäffer et al., 2008).

Models fitting particle or aggregate size with water retention properties have been developed for soils (Arya & Paris, 1981; Wu et al., 1990; Bruand et al., 2003). Most of them pointed out particle shape (which are not strictly spherical) to explain the relatively poor accuracy of the models. For growing media, particle size distribution gives more or less precise indications of the expected suitable physical properties (Bunt, 1984, Verdonck & Demeyer, 2004; Abad et al., 2005; Caron & Michel, 2021), and relationships with shrinkage properties according to particle size have never been investigated so far.

Objectives

Knowing that growing media are designed according to different particle size fractions of raw materials to offer the most suitable physical properties, works presented here aimed to respond to the following objectives:

- To describe the shrinkage curves of main representative growing media constituents, and those of different particle size fractions separated by sieving from these raw materials,
- To analyze particle arrangement (*i.e.* structure) and shrinkage properties as function of particle size and shape fractions.

Materials and methods

Growing media constituents & Sample preparation

The study was conducted on five raw materials, representing the main growing media constituents on the current market in the World (Schmilewski, 2017). Information about these materials are given in Table 1.

Table 1. Main information about raw materials studied.

Materials	Supplier ¹	Origin	Extraction / process	Bulk density ²
				g cm ⁻³
Coir (medium)	PT	Ivory Coast	Grounded	0.08
Fresh pine bark (medium)	PT	France	Screened	0.22
Wood fiber (medium)	KD	Germany	Defibrated	0.09
White peat, H2-H6 ³ (medium)	KD	Lithuania	Milled	0.11
Black peat, H6-H8 (fine)	FL	Germany	Frozen	0.18

1: FL = Floragard Vertiebs-GmbH, KD = Klasmann-Deilmann, PT = Premier Tech Horticulture France

2: Bulk density measured through EN 13041 (AFNOR, 2000) procedure

3: Von Post degree of humification of *Sphagnum* peats

Each material was sieved according to the procedure described by Durand et al. (2023a). Sieving was carried out on materials at the moisture content they are conditioned in bags by the suppliers, without prior drying, in order to avoid or limit any change of their own characteristics, like hydrophobicity occurring during a drying process. As recommended by the sieving standard method EN 15428 (AFNOR, 2007), 125 mL of material were shaken during 7 minutes using a AS 200 sieve shaker (Retsch, Haan, Germany), with 150 strokes/minutes at an amplitude of 50% (~1.5 mm). After the sieving process, each sieve is rinsed with water (approximately 1 liter) on the column using a showerhead for a few seconds. The materials retained on each sieve were collected in aluminum cans. The sieving process was repeated many times until sufficient quantities of materials per particle size fraction needed for both particle size and shape analysis and shrinkage curve experiments were obtained. Depending on the PSD of raw materials and the proportions obtained for different particle size fractions, four to five sieves were used: 5, 2, 1, 0.5, 0.2 mm. In total, five raw materials and twenty-eight particle size fractions derived from these five raw materials were then analyzed: 6 fractions for coir, pine bark and white peat, 5 for wood fiber and black peat (Table 2).

Table 2. List of samples studied.

Materials	Raw material		Particle size fractions					
	PSD ¹							
	mm		mm					
Coir	0-25	< 0.2	0.2-0.5	0.5-1	1-2	2-5	> 5	
Pine bark	0-20	< 0.2	0.2-0.5	0.5-1	1-2	2-5	> 5	
Wood fiber	2-4		< 0.5	0.5-1	1-2	2-5	> 5	
White peat	0-25	< 0.2	0.2-0.5	0.5-1	1-2	2-5	> 5	
Black peat	0-7	< 0.2	0.2-0.5	0.5-1	1-2	> 2		

1: Indicated PSD given by the suppliers

Particle size and shape measurement

A dynamic image analyzer, the QicPic (Sympatec GmbH, Germany), was used to assess the particle size and shape of raw materials and those of each of the particle size fractions collected. This dynamic image analysis device and its principle was previously described by Durand et al. (2023a). It allows from non-dried materials to analyze particle size varying between 17 μm to 33.8 mm and particle shape from 50 μm using a high-resolution camera. Size and shape of all particles of all images are then analyzed *via* the PAQXOS 4.3 software (developed by Sympatec GmbH) associated with the QicPic device. The particle distribution is weighted by projected area, corresponding to the area of the particle observed on the two-dimensional image.

As recommended by Durand et al. (2023a), the Feret_{MAX} diameter, describing the length, has been selected as indicators of particle size, whereas circularity was assessed to describe particle shape (Figure 1). A Feret diameter is a distance between two parallel tangents passing the contour of the particle. The maximum Feret's diameter (Feret_{MAX}) represents the maximum distance and is considered as the longest caliper distance (Igathinathane et al., 2009). The circularity is an indicator of the deformation of the perimeter of a particle from a circle having the same area (Wadell, 1933). An equal projection area circle (EQPC) is calculated from the measured area of the particle, and the perimeter of the EQPC (P_{EQPC}) is compared to the real perimeter (P_{Real}) of the particle (Figure 1, Eq. 1). Particle circularity is calculated as follows:

$$\text{Circularity} = \frac{2\sqrt{\text{Area} \cdot \pi}}{\text{Perimeter}} \quad (\text{Eq. 1})$$

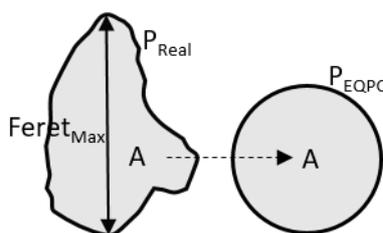


Figure 1. Schematic representation of particle length (Feret_{MAX}), and of circularity quantification (from the calculation of area, A, and perimeter, P).

Shrinkage curves

Experimental procedure and data treatment

Shrinkage curves were established using Hyprop systems (Meter, USA) equipped with two tensiometers and a scale, each being coupled with a linear vertical displacement transducer (Ametek, France). The setup, illustrated on Figure 2, allowed to measure the changes in water potential, mass, and height of sample cylinders during a free drying process. The classic Hyprop cylinders, with hermetic contours, have been replaced by porous cylinders (Negofiltres, France) of the same size. This modification allows an evaporation by the sides of the cylinder. The experiments were performed in a climatic chamber at 20°C. At least three replicates were performed per sample.

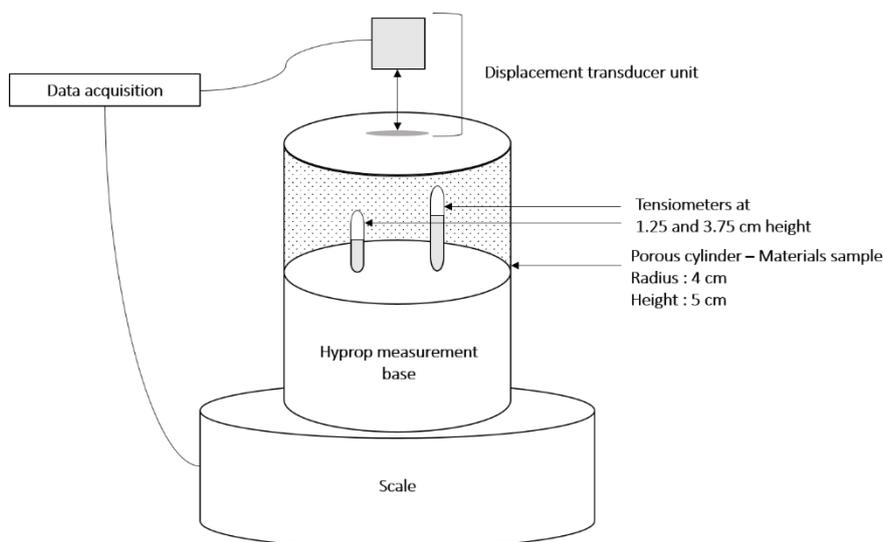


Figure 2. Experimental setup, showing the HyProp system (scale and tensiometer), the cylinder with the sample, and the displacement sensor.

The measurements were continuously recorded every 10 minutes for 10 to 15 days (when the weight of the sample cylinders was no longer being changed, *i.e.* the air-drying was reached). At the end of the experiment, the samples were then oven dried at 105°C during 48 hours to determine their dry mass, allowing to calculate the changes in water contents from the weights recorded during the drying process. At the same time, the changes in sample height measured by the transducers were then converted into sample volume using Eq. 2 (Boivin et al., 2006; Qi et al., 2011):

$$V = V_0 \left(\frac{H}{H_0} \right)^n \quad (\text{Eq. 2})$$

where V_0 , V , H_0 , and H are the volumes and the heights of the sample at the beginning and during the experiment, respectively, and n is the geometric factor. It was assumed that the deformation of the materials was isotropic, as already observed by Qi et al. (2011) for some growing media. Therefore, $n = 3$ was used to calculate the volume changes.

Shrinkage curve interpretation, key data extraction, and expression of result

Raw data were then fitted using to the XP model developed by Braudeau (1988) to partition the shrinkage into the volumetric decrease of the plasma and structural components of the pore space (Braudeau and Bruand, 1993). In details, Braudeau et al. (2004) describes four shrinkage phases: interpedal, structural, basic and residual, describing also a linear and a curvilinear part for each shrinkage phase, where the interpedal and structural shrinkages refer to the structural porosity, and the basic and residual to the plasma porosity. However, this approach was simplified (Figure 3) by ignoring the curvilinear parts of each shrinkage phase (which were quite negligible).

This frame will not be included in the paper, but is an additional information to consider in the description of types of porosity in growing media science.

In contrast, the discrepancies between the macro- and microporosity as they are defined for growing media (Drzal et al., 1999; Michel & Caron, 2021), and the structural and plasma porosity proposed by Braudeau et al (2004), should lead to adopt a new and more adapted pore classification according to their functions in growing media. Structural porosity was then partitioned into macro- and mesoporosity, where macroporosity corresponds to drainage functions defined by the air-filled porosity (< -1 kPa) and mesoporosity included the water availability for plants (between -1 and -10 kPa). Plasma porosity refers to the microporosity where water is not available, *i.e.* for < 30 μ m pore size diameters. However, the interpretation of shrinkage curves in this paper only referred to the structural and plasma porosities, and not to the concept of macro-, meso-, and microporosity.

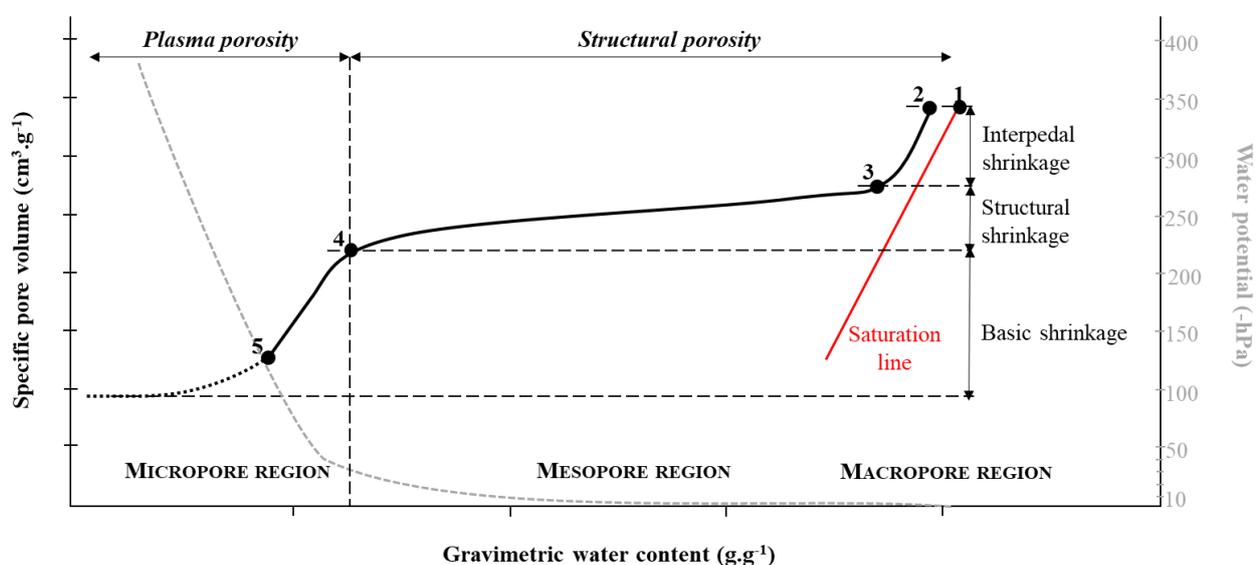


Figure 3. Schematic representation of a shrinkage curve for growing media constituents (continuous line) and interpretation keys, adapted from that of soils (Braudeau et al., 2004). Point 1 is the theoretical saturation point, 2 is the starting point of the measurements, 3 and 4 are the inflection points delimiting shrinkage phases, 5 is the last point of measurements (*i.e.* air-dried materials). The evolution of water potential during drying is represented by the dotted line. The decrease in water content is from right to left, the decrease in specific volume from top to bottom.

Sample preparation

Prior to measurements, samples were prepared according to the European standardized procedure EN 13041 (AFNOR, 2000) used the establishment of water retention curves with the sand-box method. A large polyvinyl chloride (PVC) cylinder (14 cm diameter, 14 cm height) was manually filled with the material, slowly wetted (30 min) from the bottom, saturated for 24 h, and then allowed to equilibrate to a water potential of -5 kPa for 48 h. The materials were then removed from the cylinder and homogenized for use in the experiment. They were then manually placed without packing in a column corresponding of two smaller cylinders (8 cm diameter and 5 cm height each, *i.e.* 10 cm total height), slowly rewetted from the bottom, and saturated for 24 h. Porous cylinders with a mesh size of 100 μ m (Negofiltres, France) were used rather than standard aluminum cylinders provided by the Meter company, in order to increase the air exchange surface and then to reduce the

duration of the drying process. Last, the cylinders were cautiously separated and the lower cylinder (with an initial volume of 249 cm³, deducing those of the tensiometers) was placed on the Hyprop scale. During this operation, a certain amount of water (depending on materials and particle size fractions) was drained and the material was no longer in a complete saturation state. As a consequence, the pore volume was not fully saturated at the beginning of the measurements. Loss of water is graphically observed by the differences in gravimetric water contents between the theoretical saturation point (1) and the initial measurement (2) (Figure 3).

Statistical analysis

Statistical analysis has been conducted with the software R studio version 4.1.1. The comparison of specific volumes, water contents and water potentials measured during shrinkage were carried out on all raw material and derived particle size fractions. The relationships between these parameters coming from shrinkage curves and those describing particle morphology (length and circularity) determined by dynamic image analysis were also studied.

Results

Particle size and shape

Particle length distribution according to Feret_{MAX} are presented in Figure 4, and the mean circularity of the samples are summarized in Table 1. Discrepancies in particle size were observed between those obtained by sieving and dynamic image analysis, as already described and analyzed by Durand et al. (2023a). They resulted from a more efficient particle segregation by DIA in comparison to sieving procedures, and also to the more or less elongated particle shapes of main growing media constituents, as showed by the circularity values given in Table 2. Hence, the cumulative particle length distributions showed both smaller and longer particles than the size intervals defined from the sieve apertures (Figure 4). However, the mean particle length was in accordance with the increasing size of the particle size fractions obtained by sieving (Table 2). Also, as reported by Durand et al. (2023b), decreases in mean circularity in accordance with the increasing particle length were observed for all materials.

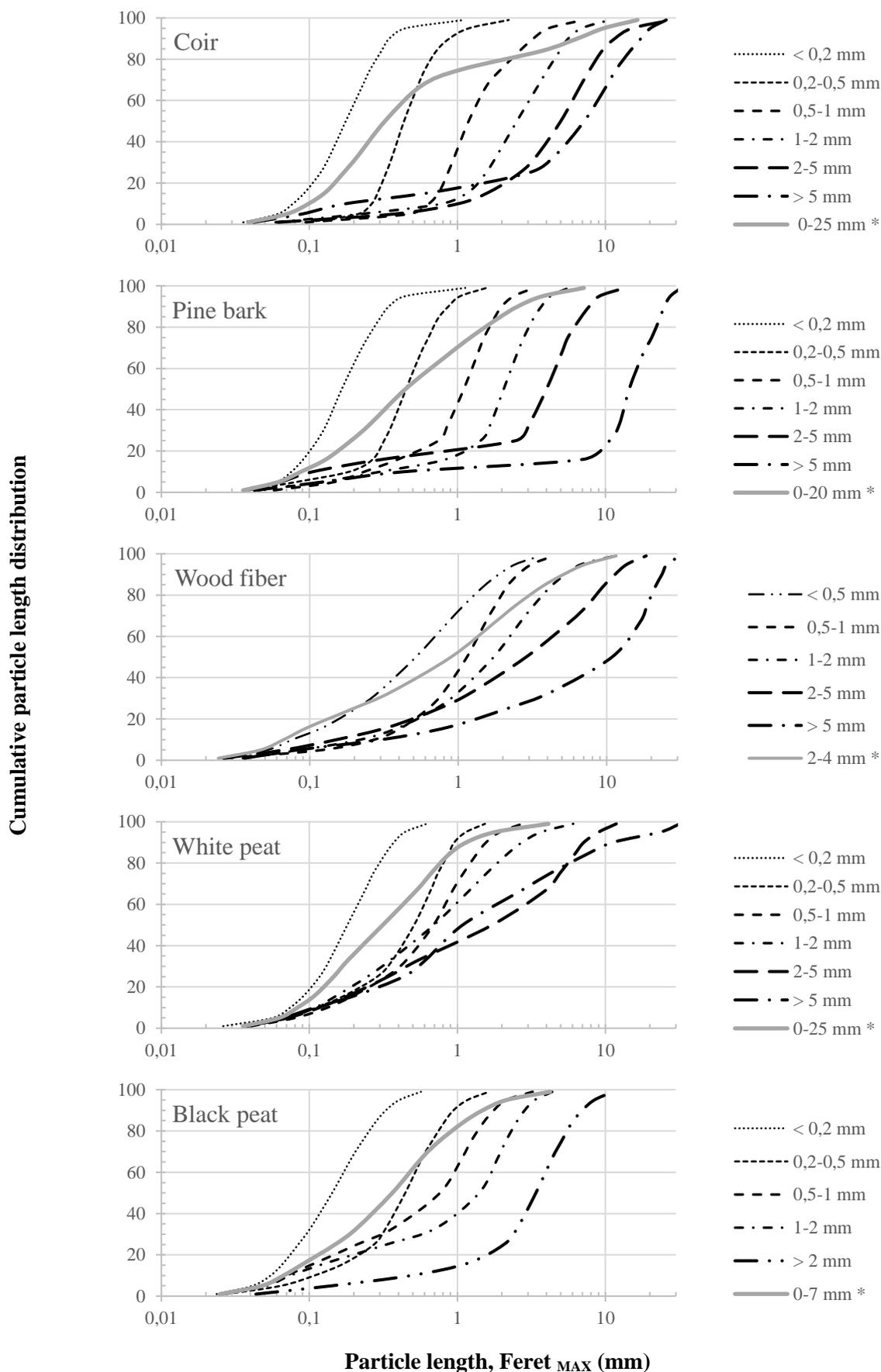


Figure 4. Cumulative particle length distribution, Feret_{MAX}, (mm), of raw materials and particle size fractions.

Table 1: Description of particle size and shape of raw materials and of their particle size fractions.

Materials	Particle size fractions	Mass proportion of the raw material	Mean particle length (Feret MAX)	Mean circularity
	mm	%	mm	
Coir	< 0.2	20.5 (0.6) ¹	0.22	0.86
	0.2-0.5	14.9 (0.4)	0.54	0.79
	0.5-1	11.9 (1.5)	1.71	0.68
	1-2	10.0 (2.1)	3.02	0.57
	2-5	13.0 (2.0)	6.01	0.45
	> 5	29.7 (2.2)	8.14	0.44
	0-25 *	100	1.81	0.75
Pine bark	< 0.2	8.8 (0.6)	0.21	0.86
	0.2-0.5	15.9 (0.4)	0.51	0.79
	0.5-1	20.6 (0.7)	1.16	0.74
	1-2	25.6 (0.7)	2.15	0.71
	2-5	26.7 (1.0)	4.14	0.70
	> 5	2.4 (0.3)	14.70	0.67
	0-20 *	100	1.00	0.80
Wood fiber	< 0.5	21.5 (0.5)	0.78	0.58
	0.5-1	14.8 (0.4)	1.31	0.48
	1-2	29.5 (1.0)	2.36	0.49
	2-5	29.4 (2.4)	4.52	0.49
	> 5	4.9 (1.1)	11.33	0.44
	2-4 *	100	1.86	0.58
White peat	< 0.2	17.4 (0.6)	0.21	0.82
	0.2-0.5	24.0 (1.2)	0.54	0.74
	0.5-1	17.4 (1.2)	0.79	0.72
	1-2	11.3 (0.6)	1.14	0.71
	2-5	15.1 (0.9)	2.93	0.67
	> 5	14.9 (1.0)	4.09	0.65
	0-25 *	100	0.56	0.76
Black peat	< 0.2	21.6 (2.9)	0.17	0.83
	0.2-0.5	22.7 (1.9)	0.51	0.75
	0.5-1	22.4 (3.4)	0.85	0.73
	1-2	16.1 (1.8)	1.42	0.70
	> 2	17.2 (1.2)	3.70	0.63
	0-7 *	100	0.64	0.80

* Raw materials with indicating particle size provided by the suppliers.

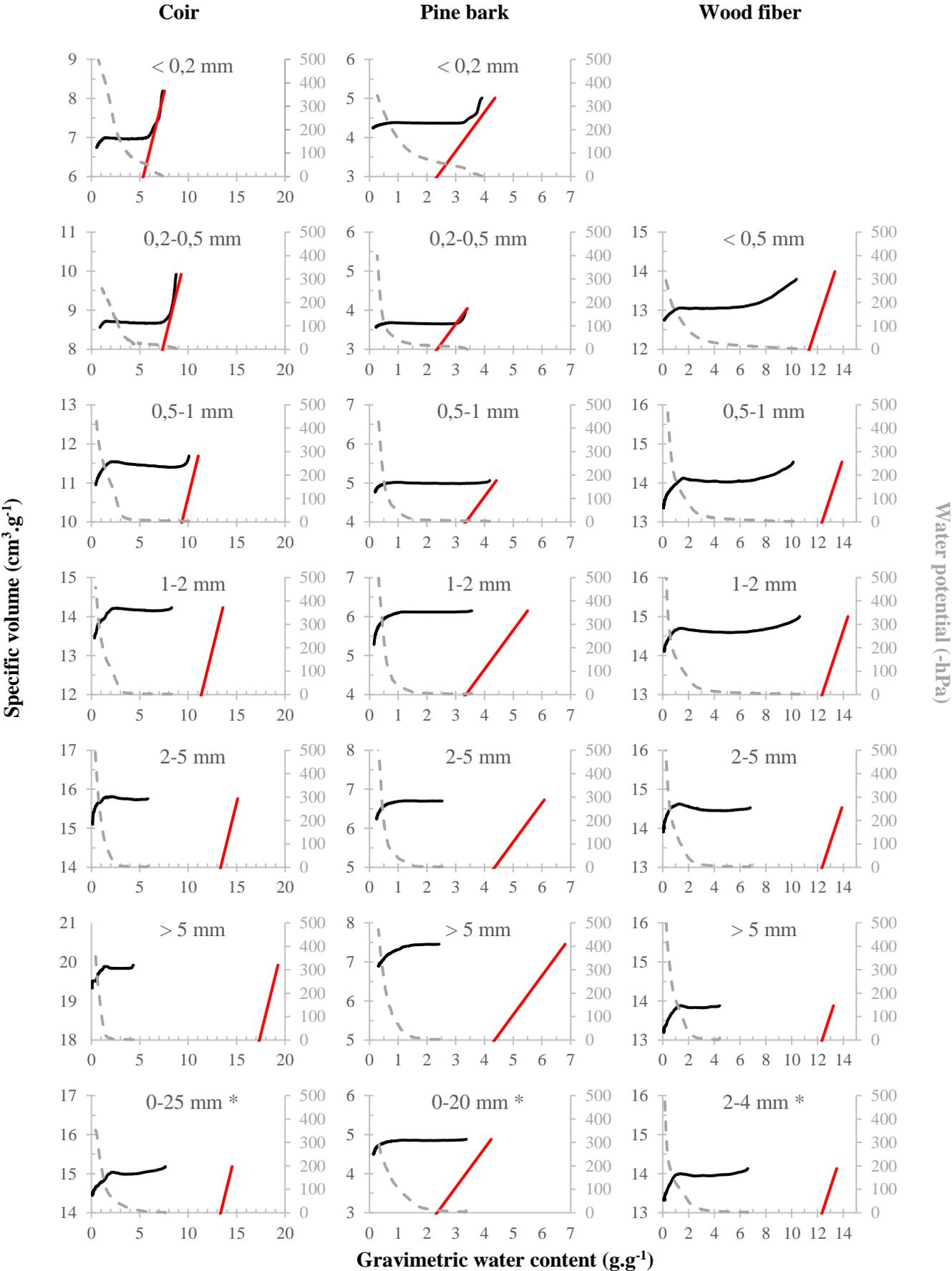
¹ Standard deviations in brackets.

Shrinkage curve description

Two main shrinkage behaviors were observed depending on particle size (Figure 5):

- For finer particle size fractions (< 0.5 mm for pine bark, < 1 mm for coir and black peat, < 2 mm for wood fiber and white peat), three successive phases were described during drying. However, the first shrinkage phase for wood fiber differed of those observed for the other materials. For wood fiber, the first shrinkage phase was low (5% vol. maximum for the < 0.5 mm fraction), and allowed air entry in the porosity. In contrast, the loss in volume was higher for the fine particle size fractions of other materials, with a maximum of 13% vol. to 31% in volume for pine bark and white peat, respectively. For them, an interpedal shrinkage was observed very close to the saturation: the loss of water lost corresponds to that of the specific volume, so that there was no air entry in the material. The magnitude of this interpedal shrinkage progressively decreased with the increasing particle size fractions. The first shrinkage phase was followed by a second drying phase characterized by the absence of structural shrinkage (except for < 0.2 mm black peat where it reached 8% vol.), then by a third phase corresponding to the basic shrinkage of the plasma porosity.
- For coarser particle size fractions, the first interpedal shrinkage previously reported for finest fractions was not observed; only two phases were described. For coir, pine bark, wood fiber, and black peat, there was no structural shrinkage during the drainage of the structural porosity; only a basic shrinkage of the plasma porosity was shown. In contrast, a continuous structural shrinkage was observed for white peat, before the basic shrinkage of its plasma porosity.

Whatever the fine or coarse particle size fractions, the basic shrinkage of the plasma started at the same water potentials around -300 hPa for white peat, and -110 hPa for wood fiber. In contrast, the values of water potentials corresponding to the beginning of the basic shrinkage decreased as the particle size fractions increased: they varied from -490 hPa to -145 hPa for black peat, from -380 hPa to -50 hPa for coir, and from -220 hPa to -10 hPa for pine bark (the first value being that of the water potential for the fraction <0.2 mm; the second for the coarsest fraction).



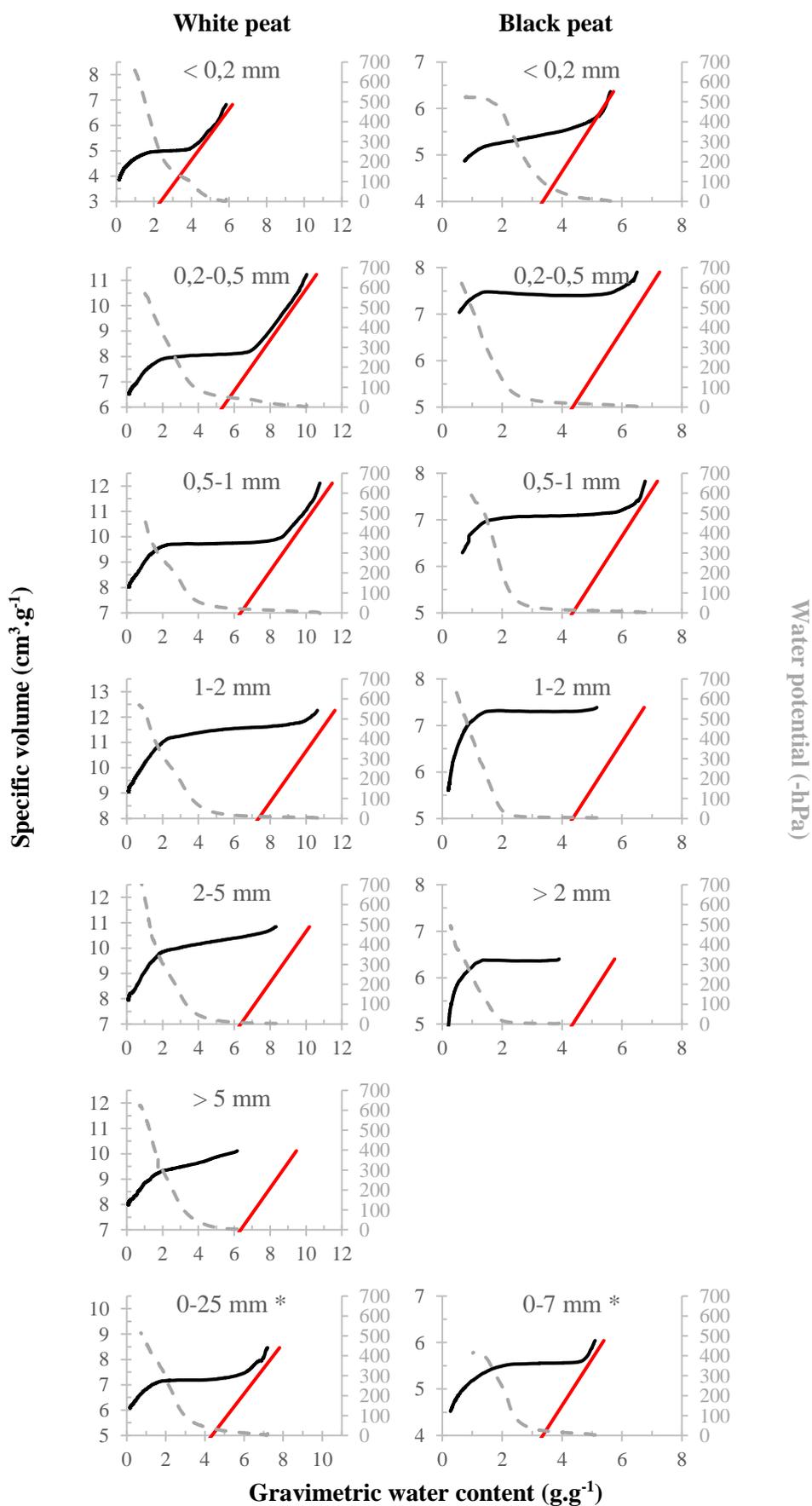


Figure 5. Shrinkage curves for raw materials and derived particle size fractions. Specific volume as a function of the gravimetric water content (black curve); water potential as a function of the gravimetric water content (grey dashed curve); saturation line (red straight line).

Structural vs plasma porosity distribution

For white peat, black peat, and wood fiber, no correlation was shown between particle size and maximal specific volume, nor its components (*i.e.*, the volumes of structural and plasma porosities) (Figure 6). The maximum value in specific volume (*i.e.*, the lowest bulk density) was reached for intermediate particle size fractions for white peat (1-2 mm), black peat (0.2-0.5 mm) and wood fiber (1-2 mm). In contrast, the specific volume increased with particle size for coir. Pine bark showed the same tendency, excepting the 0.2-0.5 mm fraction where a high proportion of fine sand was noted, and then the lowest value in specific volume was reported where (Figure 6).

The results show that the larger the particle size fraction, the lower the circularity of the particles. For coir and pine bark, the decrease in circularity goes hand in hand with the increase in the volume of structural porosity. This is not necessarily the case for wood fiber, black and white peats.

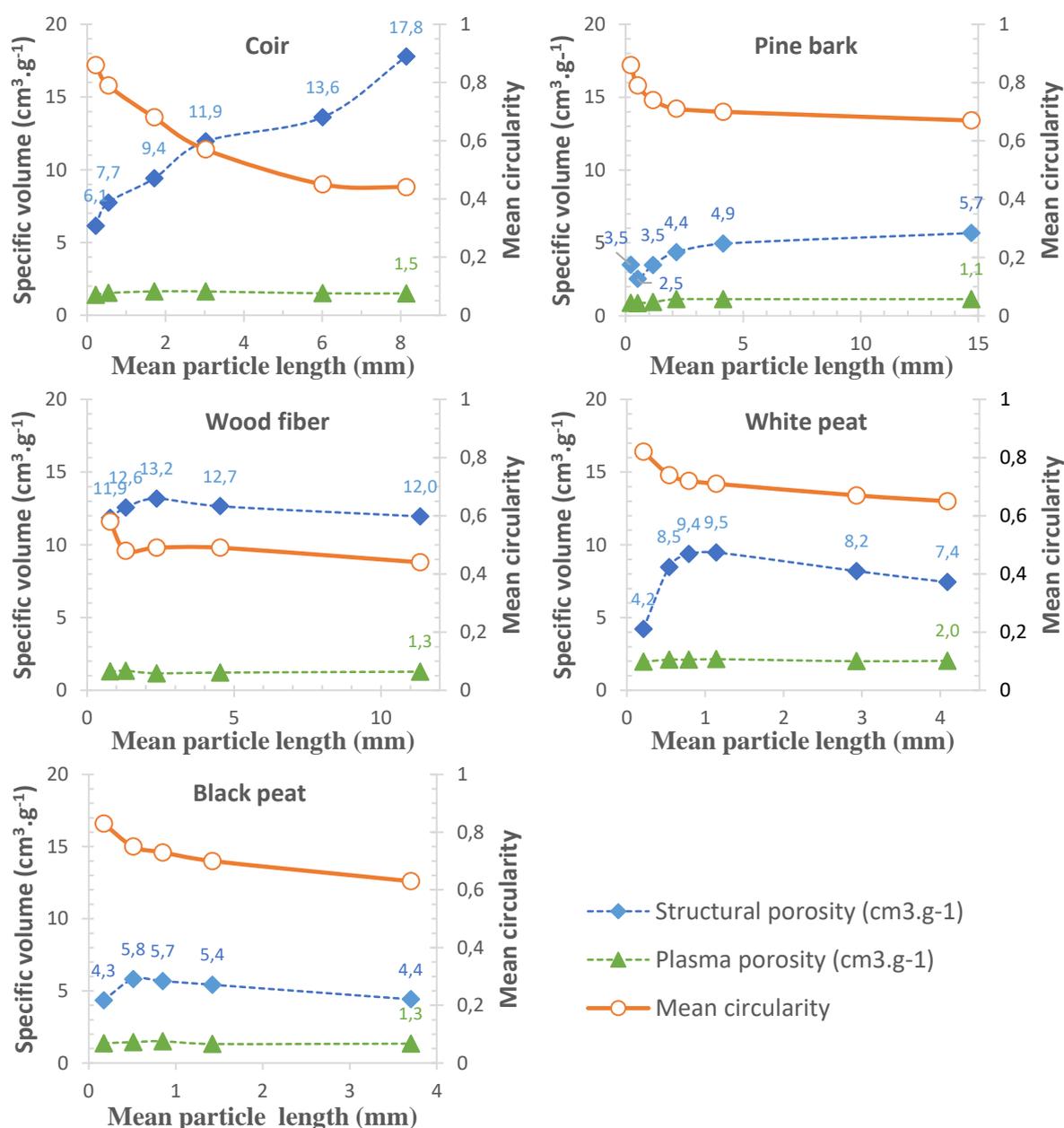


Figure 6. Changes in maximum structural and plasma porosities volumes, and in particle shape (mean circularity) according to particle size (mean particle length, $Feret_{MAX}$).

Whatever the materials and their particle size fraction, water was mainly stored in the structural porosity (with a minimum of 69% vol. of water content stored in the structural porosity for the finest fraction of white peat, and a maximum of 92% vol. for that in the coarser fraction of coir). Water content in the structural porosity largely varied depending on the materials and on particle size, but as for the specific volume, no correlation was observed between water content stored in the structural porosity and particle size for white peat, black peat, and wood fiber, in contrast with coir and pine bark (except the 0.2-0.5 mm fractions) for which water content in the structural porosity increased with particle size. However, considering all materials and particle size fractions, high significant linear correlation ($R^2 = 0.99$) was observed between the maximal specific volume (*i.e.*, at saturation) and the gravimetric water content retained in the structural porosity (Figure 7a). In contrast, water content stored in the plasma porosity was always low for all materials and particle size fractions. Water content in the plasma porosity differed a little bit depending on the type of materials, but not significantly on particle size fractions and their respective maximum specific volumes (Figure 7b).

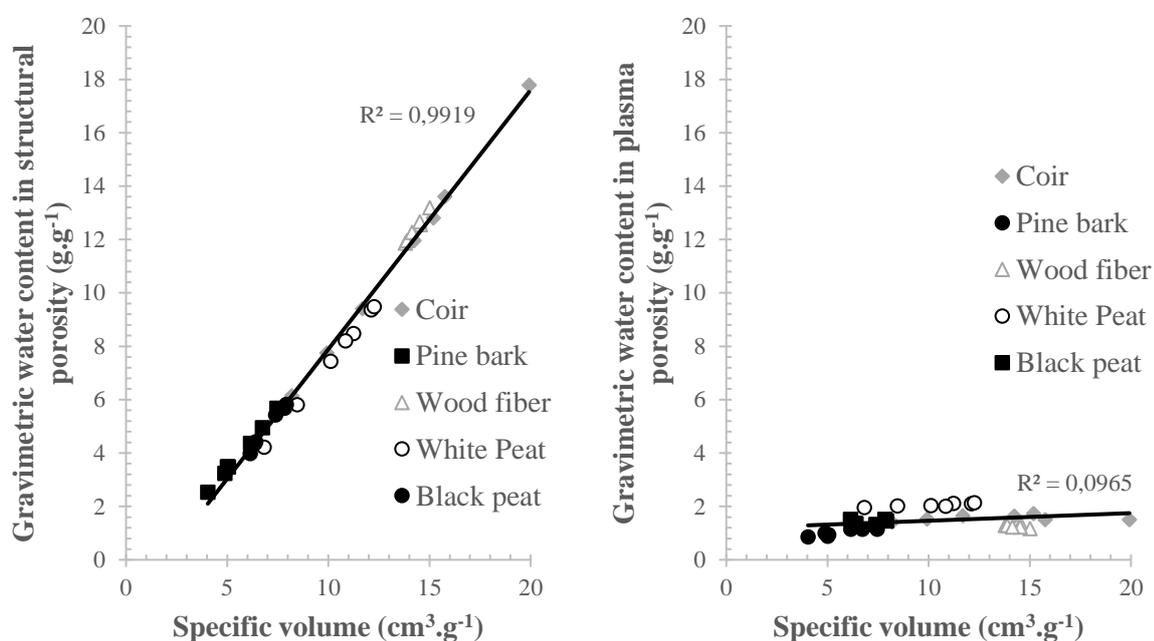


Figure 7. Gravimetric water content stored in the (a) structural porosity and (b) plasma porosity as function of maximum specific volume for raw materials and derived particle size fractions.

Shrinkage of structural porosity according to particle size and shape fractions

Relationships between the shrinkage of the structural porosity and mean particle length (Feret_{MAX}) of particle size fractions for each raw material were fitted Figure 8. The shrinkage decreased in relation with an increasing mean particle length. However, its magnitude differed according to raw materials considered. White peat showed higher shrinkage than the other materials, varying from 31% for the smaller particle size fraction to 8% for the coarser one where mean particle length reached 4 mm. In contrast, for the other raw materials and particle size fractions, only finer fractions showed significant shrinkages, with maximum values of 21% for black peat, 15% for coir, 13% for pine bark, and 5% for wood fiber. For these other materials, shrinkage was very low (< 3%) for particles larger than 1 mm.

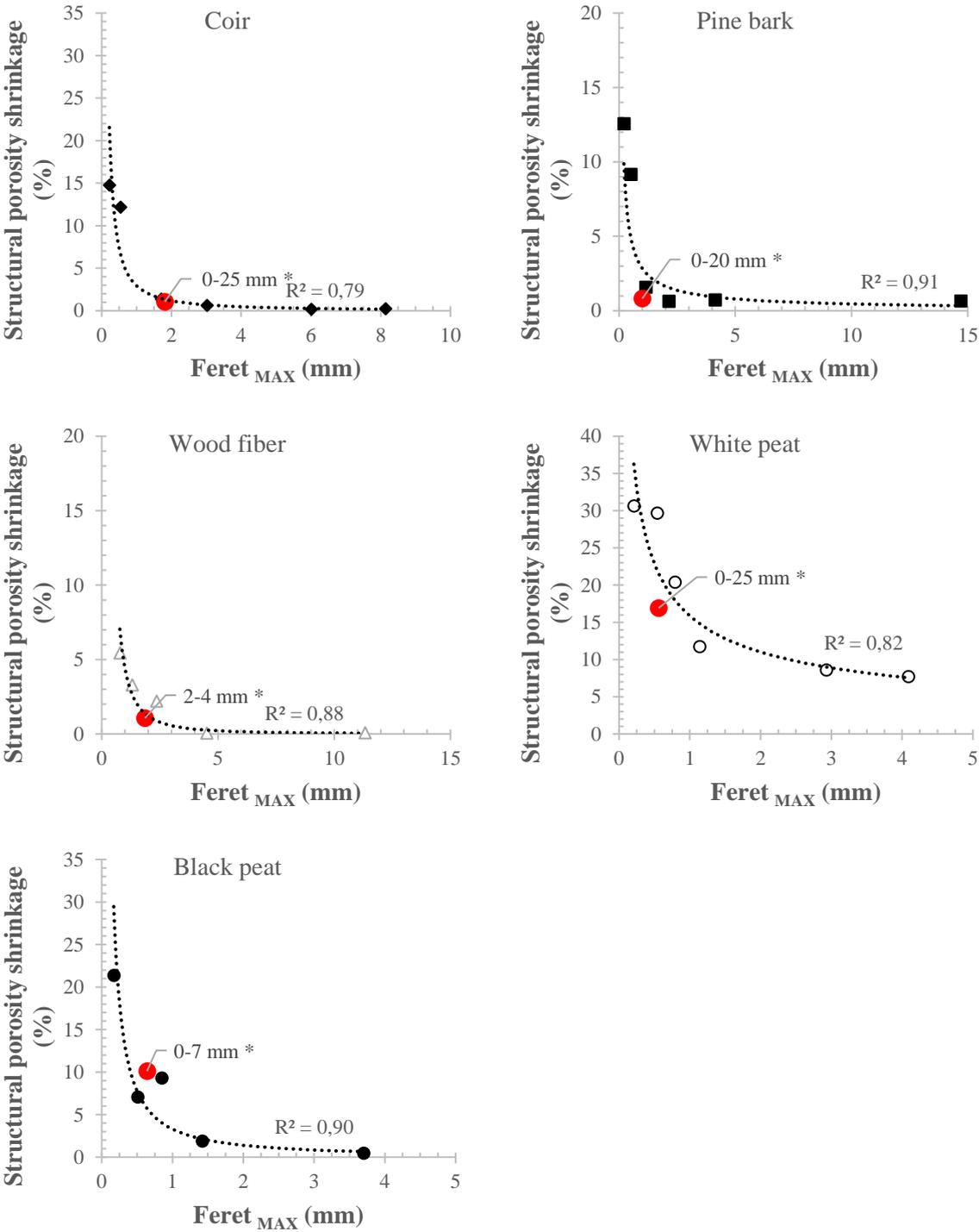


Figure 8. Shrinkage of the structural porosity as function of particle size (expressed by the mean particle length, $Feret_{MAX}$). Black and/or white symbols refer to particle size fractions; red dots to the raw materials.

Also, relationships were fitted between the shrinkage of the structural porosity and the particle shape of raw materials and derived particle size fractions, showing an increase in shrinkage with an increasing mean circularity.

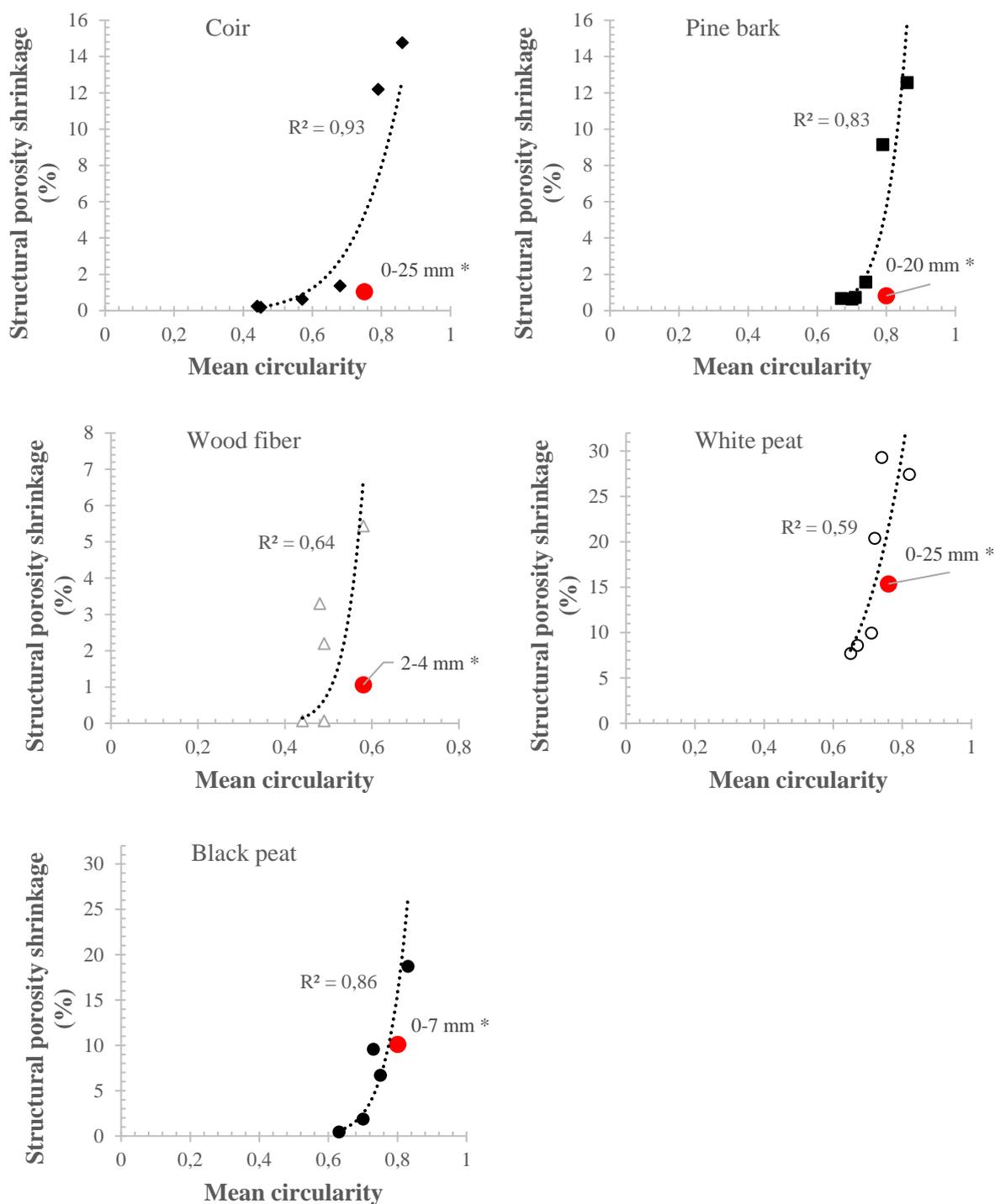


Figure 1: Shrinkage of the structural porosity as function of the mean circularity. Black and/or white symbols refer to particle size fractions; red dots to the raw materials.

Discussion

Based on the volumes of structural and plasma porosities, then on their respective ability to shrink, this work allows to propose physical meaning resulting from shrinkage curves for growing media constituents in relation with particle size and shape.

Particle arrangement: structural & plasma porosity vs particle size fractions

Volumes of structural porosity largely vary according to the nature of growing media constituents. However, two types of particle arrangement were described, depending on both particle size and shape.

For a given material, the plasma porosity (*i.e.*, intraparticle porosity) was significantly the same for all particle size fractions (Figure 7b). The differences observed in total porosity therefore only resulted in structural porosity (*i.e.*, interparticle arrangement).

- For white peat, black peat, and wood fiber, the structural porosity volume was not directly correlated with particle size, nor with particle circularity. This suggested that the structural porosity did not only depend on particle size, nor on particle circularity, but rather on the combination of both, which however varied in opposite ways. Indeed, as already observed by Durand (2023b), the higher the particle length, the lower the particle circularity, *i.e.*, the higher its elongation. Consequently, the conditions combining finest particle size (favoring lower structural porosity) and low particle circularity (probably favoring higher structural porosity) cannot be met, thus explaining the higher structural porosity observed for intermediate particle size and shape fractions.

- Coir and also pine bark (except its 0.2-0.5 mm fraction where high content in sand was reported) also showed a decreasing particle circularity as a function of an increasing particle size. But they differ from the previous materials by an increasing volume of structural porosity as the result of both increase in particle size and decrease in particle shape opposite evolutions.

That seems to suggest that a higher rigidity of coir and bark particles (containing platelets) for both increasing particle size and circularity, not favoring the compactness of the initial particle arrangement, in contrast with peats and wood fiber presenting more flexible particles in the coarser particle size fractions which are more able to be organized.

Shrinkage properties

The ability to shrink depends on the nature of growing media constituents, but also largely vary for a same material according to its particle size rather than its shape. The shrinkage of structural porosity almost exclusively concerns the smaller particle length (< 0.5 mm approximately), except for white peat where shrinkage progressively decreased with the increase in particle size but was also reported for coarser particles. Thus, in terms of structural shrinkage, the materials studied can be globally ranged in descending order as follows: white peat > black peat > coir > pine bark > wood fiber. The results seem to be in accordance with those previously reported in the literature (Qi et al., 2011; Michel et al., 2001), except for peats where higher shrinkage was usually observed on highly decomposed peat presenting finer particle size distribution than weakly decomposed peat coming from a same peatbog, which was not the case in the current study.

Shrinkage seems to be related with particle circularity, a lower circularity favor particle rearrangement, however it is difficult to confirm the single effect of particle shape. Indeed, shrinkage was mainly reported for finest particle size, and thus more circular particles. Consequently, it appears that the ability to shrink much more depend on particle size than particle shape. Nevertheless, this

hypothesis is plausible since work on sands has shown a more compact arrangement of particles with higher circularity (Millers & Henderson, 2011; Lim et al., 2012; Ulusoy, 2023).

The first shrinkage phase observed close to saturation for finer particle size fractions corresponds to an interparticle shrinkage, similar to the interpedal (*i.e.*, interaggregate) shrinkage observed for some clay pastes (Tessier, 1980) and non-rigid clayey soils (Braudeau et al., 2004). Materials with fine particles, which previously expanded during wetting, thus collapsed at the very beginning of drying, with loss of volume quite similar to that of water. There was then almost no air entry in the porosity of finest fractions in this stage. Note that the discrepancy observed between shrinkage curves and saturation line were probably due to the experimental procedure, where the use of porous cylinders and their installation into the Hyprop system allowed free drainage of a certain amount of water. Logically, according to the Laplace-Jurin law, free drainage and thus this discrepancy increased with particle size, while the amplitude of interparticle shrinkage progressively decreased, and was not observed for coarser particle size fractions.

Once consolidated after the first shrinkage for finer particle size fractions or without the first shrinkage for coarser fractions, the emptying of the remaining water stored in the structural porosity is characterized by the absence or a low structural shrinkage, allowing a large air entry into the system and the progressive and total loss of water located in the interparticle porosity.

The loss of water retained in the inner-particle porosity and absorbed on the particles surface (*i.e.*, plasma porosity) is thereafter accompanied by a volumetric shrinkage (called basic shrinkage). This latter was observed on all materials and particle size fractions; it even represented the only loss of volume for the coarser particle size fractions. The emptying of peat hydrocysts, which leads to particle shrinkage (especially for fibers) has already been reported to explain the shrinkage of the internal porosity of the particles (Valat et al., 1991).

Conclusion

Few explored so far, this work aimed to finely describe and analyze the particle arrangement and shrinkage properties of different growing media constituents expressed in terms of changes in structural and plasma porosity, as function of their particle size and shape.

Although the volumes and proportions of plasma and structural porosity as well as the ability to shrink largely vary according to the nature of growing media constituents, they also highly depend on particle length, but also, in a lesser degree, on particle circularity.

Relationships between respective volumes of structural and plasma porosity, as well as shrinkage of structural porosity, and particle mean length (and circularity) have been established and quantified. They revealed that changes in particle arrangement according to particle size only result in those of structural porosity, and that shrinkage mainly concerns the finest particle size fractions (mean particle length <0.5 mm), except for white peat for which a progressive decrease in shrinkage was also observed for increasing particle length. Particle arrangement and shrinkage of the structural porosity depend on both particle size and circularity, which however vary in opposite ways. The resulting led to higher structural porosity in intermediate particle size fractions for fiber-based materials (black and

white peats, and wood fiber), and conversely, and in coarser particle size fractions for materials containing platelets (bark and coir).

This fine analysis of shrinkage curves provides valuable but also quantitative information about particle arrangement according to particle size and shape, that could contribute to a better selection of raw materials and particle size fractions for the growing media industry.

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Paper 4: Advances in substrate particle characterization using dynamic image analysis compared to sieving procedure for predicting water retention properties

Durand S., Jackson B.E., Fonteno W.C., Michel J.C., 2022. Advances in substrate particle characterization using dynamic image analysis compared to sieving procedure for predicting water retention properties. *Acta Horticulturae*, accepted, in press.

Abstract

Water/air retention and flow properties in horticultural substrates depend on pores which are created by particle arrangement and particle morphology. Manufacturers mainly select substrate components based on particle size determined through sieving processes. However, sieving methods are most suitable to characterize granular materials (with 1:1, length:width ratio). Particle size distribution of substrate components may be improperly assessed due to their much larger diversity of particle morphology (fibers, plates, etc.).

Particle width and shape of numerous substrate components (white and black peats, bark, wood fiber, perlite, compost) were measured using dynamic image analysis, and compared with the mean particle size determined from the EN15428 sieving method.

Dynamic image analysis showed much smaller mean particle width in comparison to sieving. It also provided additional information about particle length, confirming the non-granular shape of most of substrate components. Relationships between particle morphology and water holding capacity were explored. A strong correlation was observed between mean particle length and water holding capacity. This work reports the strong interest to deeply investigate particle morphology using dynamic image analysis for predicting physical properties.

Introduction

Substrate manufacturers engineer the particle size of substrate components to provide the plant root system a suitable physical environment. Particle size distribution (PSD) in part determines particle arrangement of substrate constituents, and is one of the main factors used to describe physical properties. Relationships between PSD and physical properties have already been developed, indicating 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; Owen & Altland, 2008; Fields et al., 2015). However, there is not a real consensus on the effect of specific particle size fractions on water and air retention properties. Caron et al. (2005) reported that increase in particle size was not correlated to gas diffusivity in substrates resulting from both increase in air filled porosity and decrease in pore connectivity and then pore effectiveness.

Sieving procedures are the most common methods for determining PSD, separating particles according to their 2nd largest dimension, *i.e.*, their width (Igathinathane et al., 2009; Ulusoy & Igathinathane, 2016; Bartley, 2019). These methods are relevant for granular particles, but their

accuracy largely decreases with increasing elongation of substrate particles (Gil et al., 2014; Bartley, 2019). Moreover, they do not provide information about particle length. Consequently, sieving methods are limited in describing PSD for most horticultural substrate components showing a large diversity of irregular shapes with fibers, chips, and plates, which are far from spherical (Durand et al., 2021).

In contrast, tools based on dynamic image analysis (DIA) have been recently used for characterizing substrate particle size and shape (Bartley, 2019; Durand et al., 2021; Nguyen et al., 2022). Tools differ: 1) by method of dispersing the particles (dry or wet) and 2) particle image resolution. Also, the principles of DIA methods also are largely different to those of sieving methods, and Bartley (2019) showed that the particle size and distributions obtained by image analysis differed from sieving

The objectives of this study were: 1) to compare particle size of several substrate components using the EN15428 standard sieving procedure and by dynamic image analysis, 2) highlight the relevance of dynamic image analysis for both an expanded description of substrate particle and prediction of water retention properties.

Materials and methods

Samples

Experiments were carried out on 19 raw materials, representing the main growing media constituents in the current European market. Information about these materials are given in Table 1.

Table 1. Studied materials.

No	Materials	Supplier ¹	Origin	Extraction / process	Bulk density ²	Indicated PSD ³
					g cm ⁻³	mm
1	White peat, fine, H5 ⁴	PTH	Ireland	Milled, screened	0.10	0-5
2	White peat, fine, H3-H6	KD	Lithuania	Milled	0.10	0-7
3	White peat, fine, H2-H5	FLO	Latvia	Milled	0.10	0-5
4	White peat, fine, H2-H5	FLO	Germany	Sod	0.08	0-7
5	White peat, fine, H2-H5	KD	Lithuania	Sod	0.11	0-7
6	White peat, medium, H3-H6	KD	Lithuania	Milled	0.11	0-25
7	White peat, medium, H2-H5	FLO	Latvia	Milled	0.10	5-20
8	Black peat, H6-H8	KD	Lithuania	Frozen, milled, sieved	0.17	0-5
9	Black peat, H5-H8	FLO	Germany	Frozen	0.18	0-7
10	Sedge peat	ETF	France	Excaved	0.24	0-10
11	Coir, fine	PTH	Sri Lanka	Ground, sieved	0.08	0-5
12	Coco fiber, medium	PTH	Ivory Coast		0.08	N/A
13	Wood fiber, fine	KD	Germany	Defibrated	0.08	0-2
14	Wood fiber, medium	KD	Germany	Defibrated	0.09	2-4
15	Wood fiber, medium	FLO	Germany		0.09	N/A
16	Fresh pine bark, fine	PTH	France	Screened	0.22	0-5
17	Composted pine bark, fine	PTH	France		0.25	0-5
18	Green waste compost	KD	Germany		0.50	0-5
19	Perlite, coarse	KD	Germany		0.10	1-7.5

¹ ETB = EVADEA Tourbières de France, FLO = Floragard Vertiebs-GmbH, KD = Klasmann-Deilmann, PTH = Premier Tech Horticulture France

² measured through EN 13041 procedure (2000) ; ³ PSD indicated by the suppliers ; ⁴ Von Post degree of humification

Methods

Dry sieving - EN 15428 standard method

Dry sieving analysis was carried out using the EN 15428 standard method (2007). However, the numbers of sieves, with square aperture, was increased for a more detailed PSD analysis, passing from four sieves for the standard method (8, 4, 2, 1 mm aperture) to eight sieves (8, 5, 4, 2, 1, 0,5, 0,2, 0,05 mm). 125 mL of air-dried materials (<15% moisture content by mass) were shaken during 7 minutes with a sieve shaker AS 200 (Retsch, Haan, Germany). The materials retained on each sieve were collected and weighted; three repetitions for each raw material. Arithmetic mean particle size was assessed through Gradistat software (Blott & Pye, 2001) version 16.0 (2020).

Dynamic image analysis

Measurements were conducted with the QicPic dynamic image analyzer (Sympatec GmbH, Germany). The device can detect particle sizes in a range from 17 μm to 33.8 mm. Length and width of each particle were assessed from the $\text{Feret}_{\text{MAX}}$ and $\text{Chord}_{\text{MIN}}$ diameters, respectively (Nguyen et al., 2022). The particle length and width is shown in Figure 1. $\text{Feret}_{\text{MAX}}$ is the maximal distance between two parallel tangents of the particle contour. Chord width is defined by the straight distance of two points of the particle contour. The software analyzes the particle image by rotating the image 180 degrees in 20 separate 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.

In contrast with the EN15428 standard procedure where sieving is carried out on air-dried materials, DIA is implemented on wet materials previously and precisely dispersed in water. Approximately 2 to 3 grams of material were stirred with ~10-15 L water in a tank for 10 minutes, then passed through the QicPic in a constant flow controlled by a peristaltic pump, and circulated through the flow cell equipped with a camera for continuous image recording. Three repetitions were carried out, representing 10^7 particles per replicate. Results were then analyzed with the associated software, PAQXOS. The weighting of each particle is done according to the projected area of the particles.

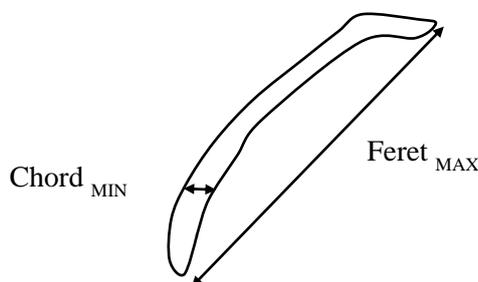


Figure 1. Particle width and length, represented by $\text{Chord}_{\text{MIN}}$ and $\text{Feret}_{\text{MAX}}$ diameters, respectively.

Water retention properties

Water retention curves were performed according to standard method EN13041 (2000), for which bulk density (BD), total porosity (TP), air-filled porosity (AFP), water holding capacity (WHC) and available water (AW) were calculated. The principle consists in putting substrate-filled cylinders into

equilibrium at different and successive water potentials using a suction table, *i.e.*, -1 kPa; -3.2 kPa; -5 kPa and -10 kPa, and to determine their volumetric water content at these values of water potentials. Four replicates per material were carried out.

Results

Comparison EN15428 sieving procedure vs DIA

Mean particle size measured by dry sieving were much higher than particle width from Chord_{MIN} diameter assessed by DIA (Table 2.) Particle dispersion in water prior to DIA may have improved the separation of individual particles, whereas particle segregation is more difficult and probably less thorough during the sieving of air-dried raw materials.

Moreover, the sieving procedure at best separates particles based on the 2nd largest particle dimension (equivalent to its width). However, the length:width ratio has been shown to prevent particles with more than 1:1 ratio from segregating at this smaller dimension (Bartley et al., 2019). DIA assessed particle length independently from width, reducing the influence of the L:W ratio and providing more detailed information about materials.

Table 2. Mean particle dimensions measured from sieving and dynamic image analysis (DIA).

No	Materials	Mean particle Feret	Mean particle	Mean particle size
		MAX (DIA)	Chord _{MIN} (DIA)	(EN 15428 sieving)
		μm	μm	μm
1	IE white peat, fine H5 ³	811	346	938
2	LT white peat, fine H3-H6	519	203	2535
3	LV white peat, fine H2-H5	1208	480	1140
4	DE white peat, fine H2-H5	821	247	1388
5	LT white peat, fine H2-H5	488	198	1588
6	LT white peat, medium H3-H6	557	225	3032
7	LV white peat, medium H2-H5	1894	679	5405
8	LT black peat H6-H8	490	230	1145
9	DE black peat H5-H8	635	328	1028
10	FR sedge peat	233	119	2460
11	Coir, fine	715	364	974
12	Coco fiber, medium	1813	281	2063
13	Wood fiber, fine	1707	475	1600
14	Wood fiber, medium	2428	712	2113
15	Wood fiber, medium	2961	823	2505
16	Fresh pine bark, fine	1573	718	1859
17	Composted pine bark, fine	700	332	1848
18	Green waste compost	787	282	1228
19	Perlite, coarse	3590	3176	2886

The differences in particle mean size was also influenced by the shapes of raw materials studied. Most of them are mostly non-spherical, as showed by large differences between mean particle width and length. Perlite was the exception, where particle dimensions measured from sieving and DIA are in the same order. Perlite was the most granular material tested with an average L:W ratio of 1.1. Except for perlite, the material L:W ratio ranged from approximately 2 to over 6. Indeed, except for perlite, the mean particle size determined by sieving was similar or exceeded the length of the particle determined by DIA. Providing both length and width for each particle indicates the usefulness of DIA for characterizing PSD of substrate components.

DIA vs water holding capacity (WHC)

An empirical model, based on the similar mathematical expression of the van Genuchten model (1980), was applied to describe the effect on water holding capacity (WHC) and particle dimensions (Figure 2). Mean particle size measured from dry sieving procedure showed little relation the WHC ($R^2=0,12$) (Figure 2a). DIA showed that the greater the mean particle width and length, the lower the WHC (Figure 2b and 2c). The best fit was between WHC and mean particle length ($R^2=0.87$), followed by mean particle width from DIA ($R^2=0.60$). In contrast to the sieving procedure, particle length and to a lesser extent, particle width determined by DIA may be another facet in determining WHC in substrates.

Discussion and conclusion

In comparison with sieving, DIA provided more information by describing each particle in both width and length and then confirmed the non-granular shapes for most of raw materials tested.

A possibly strong relationship between particle length and water holding capacity has been shown for a large diversity of raw materials used as growing media constituents, confirming that PSD largely influences substrates physical properties. Those also depend on other parameters, in particular bulk density when filling of pots (Heiskanen et al., 1996). However, particle length might be considered as an indicator of water retention properties. Further investigations will be extended to mixes, and will also explore relationships between particle size (length and width) and transfer properties, *i.e.*, gas diffusivity and hydraulic conductivity.

This work has demonstrated promising interest in DIA tools for measuring particle size, and their length in particular. Although informative and easy to implement, standard sieving procedures is more limited for non-granular materials in predicting substrate physical properties, because they do not describe particle morphology. DIA may offer an additional approach for substrate manufacturers to better engineer and select raw materials on a particle morphology basis.

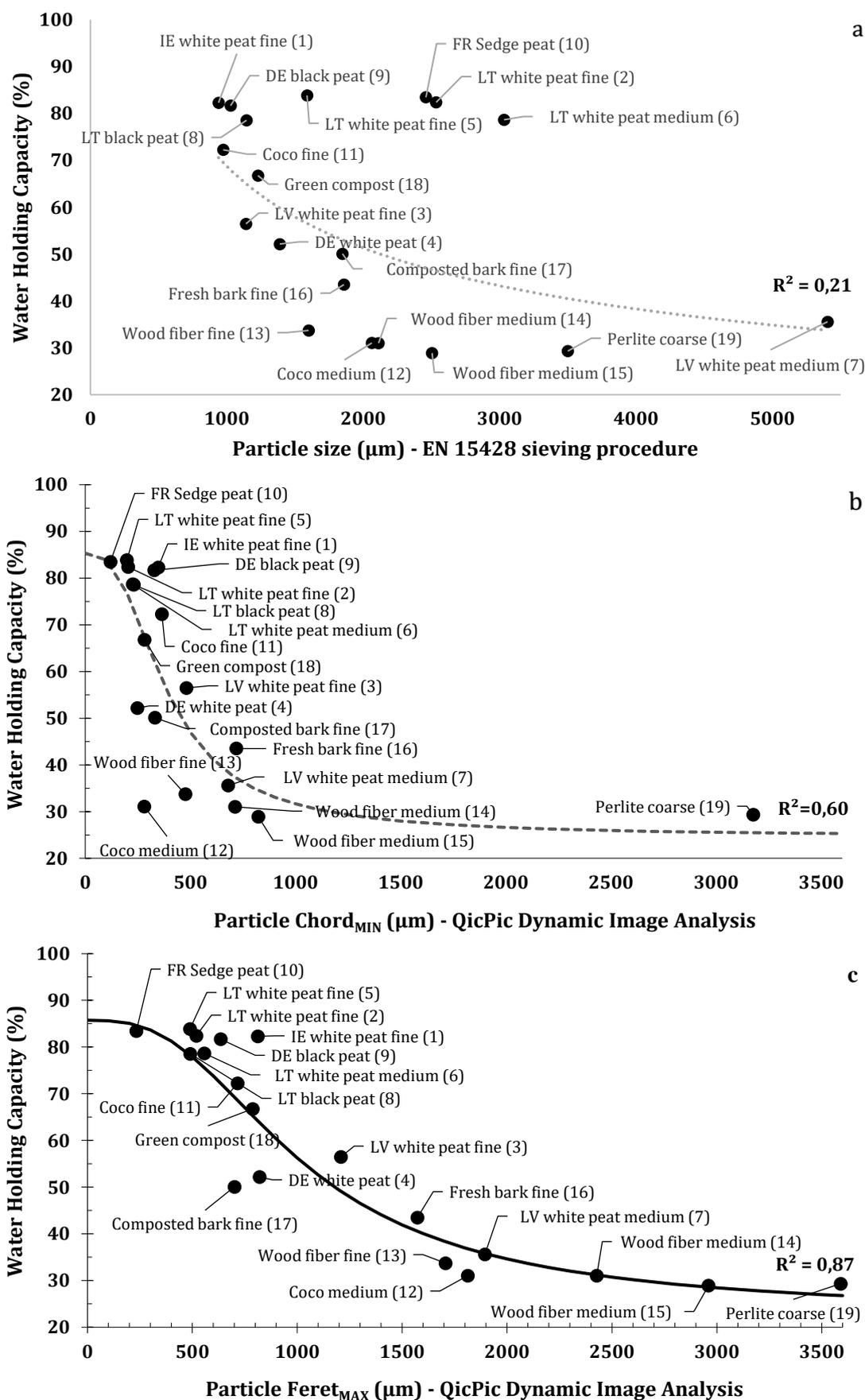


Figure 2. Water holding Capacity as a function of (a) mean particle size determined by EN15428 sieving procedure, (b) mean particle width ($Chord_{MIN}$) and (c) mean particle length ($Feret_{MAX}$) measured by dynamic image analysis.

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Paper 5: Predicting some static physical properties of growing media constituents from their mean particle length

S. Durand, W.C. Fonteno, & J.-C. Michel, soon submitted to *Scientia Horticulturae*

Abstract

A better knowledge of the relationship between physical properties and particle morphology may help to optimize the selection of raw materials, and of particle size fractions, used as growing media constituents. In the past, works have described the outlines of these relations, most of them based on sieving procedures to characterize particle size distribution. They have shown contradictory results, due to the different methods used, size fractions selected, and physical properties measured. Also, sieve analysis is less accurate for non-spherical particles, which is the case for many growing media constituents, and recent works have promoted the use of dynamic image analysis (DIA) tool to precisely analysis particle length and width.

In order to more precisely understand relationships between particle morphology and physical properties, five raw materials were chosen (white and black peats, coir, pine bark, and wood fiber), and sieved to obtain various particle size fractions as carefully as possible. For each particle size fraction, and for the raw materials, the mean weight diameter was calculated, whereas mean particle length and width were determined using a DIA tool, the QicPic device. Also, equilibrium-based physical properties were assessed from water retention curves established using Hyprop systems.

Results confirmed that the larger the particle size, the higher the air-filled porosity (AFP) and the lower the water holding capacity (WHC), but no correlation was found between particle size and easily available water (EAW). Variations in physical properties mainly rather concern the smaller particle size fractions (< 1 mm for peats and bark, and < 2 mm for coir and wood fiber), and conversely, few or no variations were observed for the particle coarser size fractions. Relationships were successfully fitted using regression model, whatever the particle size descriptor used. Among them, mean particle length was identified as the most relevant parameter for predicting WHC of raw materials.

Introduction

Growing media manufacturers engineer growing media to provide the plant root system a suitable physical environment. Different industrial processes are used to define the quality of materials: separation by sieving or screening, modifying the size by grinding, cutting, and defibration or expansion of raw materials. These actions culminate in the manufacture of particles with (hopefully) predefined size ranges, which modify the shape and surface aspects of the particles. There is an increased need to introduce new raw materials into growing media selection palette (Blok et al., 2021) and to optimize their morphology to obtain better performance.

Particle size distribution (PSD), in part, determines particle arrangement, and is one of the common procedures used to describe physical properties of growing media (Verdonck & Demeyer, 2004). Many references have been published since the 80's, and usually concluded that the larger the

particle size, the higher the air-filled porosity (AFP) and the lower water holding capacity (WHC). However, their values vary widely depending on the materials. Table 1 reviews the literature on the topic, and shows a diversity of approaches used. Indeed, the works were performed for different types of materials and different particle size ranges (raw materials, fractionated materials, blends), with respect to different physical properties, measured via different protocols; and different parameters used to characterize the particle size: arithmetic or geometric mean weight diameter (Kemper & Rosenau, 1986), coarseness index (Richards et al., 1986) or mass proportion of a given fraction.

This review reveals contradictory conclusions due to the different approaches. Some authors claim that EAW, AW, WHC or AFP are related to particle size, showing linear (Abad et al., 2005; Prasad et al., 2004) or quadratic/power regressions (Verhagen, 1997; Richards et al., 1986; Verdonck & Demeyer, 2004; Durand et al., 2022), whereas others did not (Caron et al., 2005; Handreck, 1983). Also, some argue that some relationships apply to some blends (Richards et al., 1986; Naasz & Bussière, 2011) or not (Prasad et al., 2004). Finally, Review suggest that effects of the particle size on the physical properties of growing media are limited to certain ranges in particle size, and thus that no significant differences are observed when threshold values are reached, (Handreck, 1983; Nkongolo & Caron, 1999; Fields et al., 2015; Durand et al., 2022).

Although solid phase and pore phase organization and, consequently, physical properties, are influenced by PSD, other parameters affect water and air retention and flow properties (Boudreault et al., 2014; Caron & Michel, 2017). Mixing and potting operations can largely alter the bulk density (Gruda & Schnitzler, 2004) and affect the integrity of materials, changing their particle size (Heiskanen, 1994; Heiskanen et al., 1996). Physical properties can be greatly affected by container geometry (Bilderback & Fonteno, 1987; Raviv et al., 2002; Owens & Altland, 2008). Changes in physical properties during cultivation occur due to drying/wetting cycles, related to the irrigation management and root development in the growing media (Michel & Kerloch, 2017; Michel, 2019). Jackson et al. (2009) also observed changes in air and water retention for wood fiber and bark growing media before and after cultivation, as well as a decrease in particle size.

In the references cited in Table 1, PSD has been determined by sieving methods, except that of Durand et al. (2022) who used the Dynamic Image Analysis (DIA) method. Sieving procedures are the most common methods used by manufacturers and researchers for PSD analysis of growing media. Various procedures are used; some of them being standardized (ISO, 1988, AFNOR, 2007). These methods are easy and fast to implement, reliable, cost effective. However, several authors have shown that this method is less descriptive, especially for elongated particles (Gil et al., 2014; Bartley et al., 2022). Recently, DIA tools have been introduced to describe particle morphology of materials used as growing media (Bartley, 2019; Nguyen et al., 2022; Durand et al., 2022; Durand et al., 2023a; Durand et al., 2023b). This method consists of analyzing individual randomly oriented particles captured by a camera (Trubetskaya et al., 2017), allowing a multidimensional characterization of each particle size and shape (length, width, circularity, convexity, elongation, roundness). Using this method, Durand et al (2022) showed that the mean particle length is a more precise indicator than mean particle width than mean weight diameter to describe the relationship between particle size and water and air retention of a large diversity of raw materials.

Table 1. State of the art: relations between particle size and physical properties of growing media constituents.

References	Materials studied	Variables used for describing particle size	Finding regarding physical properties
Handreck, 1983	Pure and mixture of fractionated pine bark. Fractionated sand Mixture of sand and pine bark	Intervals of individual fractions Proportion of particle in a given fraction	<ul style="list-style-type: none"> • < 0.5 mm particles (%) have the greater effect on AFP and AW • \nearrow 0.1-0.25 mm particles \Leftrightarrow \searrow AFP, \nearrow AW to a greater extent than particle range 0.25 - 0.5 and < 0.1 mm • \nearrow < 0.1 mm particles (%) \Leftrightarrow \searrow AFP, \searrow AW • Particle ranging from 0.1 to 0.25 mm have twice the AW of 0.25 to 0.5 mm • Pine bark particle < 0.25 mm have higher AW than sand of the same size range
Bunt, 1984	Raw peats Minerals: perlite, vermiculite, clay, sand Peat:Minerals blends	Raw ¹	<ul style="list-style-type: none"> • No correlation between TPS and BD with particle size of minerals • Mixture of fine mineral with peat has lower AFP than individual mineral or peats • Coarse grade of minerals reduces the EAW (> 25% by vol.) and the WHC; EAW not affected by fine grade of mineral
Richards, 1986	Mixtures of pine bark, sand, coal	> 1 mm particles (%)	<ul style="list-style-type: none"> • \nearrow > 2 mm particles (%) \Leftrightarrow \searrow WHC, \nearrow AFP • Linear correlation with physical properties
Limbers & Rehme, 1997	Screened (star) sod and milled peat at 10, 20 and 50 mm	> 5 mm and < 0.2 particles (%)	<ul style="list-style-type: none"> • AFP is related to particle content of < 0.2 and > 5 mm • \nearrow > 5 mm particles increase the AFP, conversely for \nearrow 0.2 mm particles
Verhagen, 1997	Raw and screened (<16 mm) milled peat	< 1 mm particles (%)	<ul style="list-style-type: none"> • Power/quadratic relationship with AFP • Separate components are not useful to predict the AFP of the mixture
Nkongolo & Caron, 1999	Mixture of peat (50%), gravel (10%), with various fraction of wood bark (40%)	Arithmetic mean weight diameter	<ul style="list-style-type: none"> • AFP constant for > 2 mm particles • Pore tortuosity increases and gas diffusivity decreases with increasing size of bark fractions (Gas diffusivity of 1 -2 & 2 - 4 mm > 8 - 16 & 8 -25 mm)
Gruda et al., 2001	Wood fiber	< 1 mm particles (%)	<ul style="list-style-type: none"> • Quadratic relation with WHC
Prasad & Ni Chualain, 2004	Raw and mixed peat. Mixes of peat and coir, bark, composted green waste	< 1 mm particles (%)	<ul style="list-style-type: none"> • linear correlation \nearrow < 1 mm particles (%) \Leftrightarrow \nearrow AFP (determined at -5 kPa) for peat • no correlation for mixes
Verdonck & Demeyer, 2004	Raw and fractionated peat, composted bark, perlite. Mixes of peats, composted bark peat/perlite	Proportion of particle in a given fraction	<ul style="list-style-type: none"> • \searrow particle size fraction \Leftrightarrow \nearrow EAW, \searrow AFP
Abad et al., 2005	Peats Coir	Geometric mean diameter > 1 mm particles (%)	<ul style="list-style-type: none"> • 0.125-1 mm particles (%) have a high impact on WHC, EAW, AFP conversely to smaller and grater particles. • \nearrow > 1 mm particles (%) \Leftrightarrow \searrow EAW, \searrow WHC, \nearrow AFP • \nearrow particle size \Leftrightarrow \searrow hydraulic conductivity
Caron et al., 2005	Mixes of bark, peat, perlite, coir, sand, wood finer with varying proportion of coarse particle	Arithmetic mean weight diameter	<ul style="list-style-type: none"> • \nearrow coarse particles (%) \Leftrightarrow \nearrow AFP; \nearrow < 1 mm particles (%) \Leftrightarrow \searrow AFP • Maximum gas diffusivity with particles from 2 to 4 mm except for fibrous materials • Not correlated with AW and gas diffusivity
Naasz & Bussière, 2011	Mixtures of peat, peat-perlite and peat-sawdust	Arithmetic mean weight diameter < 0.3 mm and 0.8-2 mm fractions (%)	<ul style="list-style-type: none"> • \nearrow < 0.3 mm (%), \searrow 0.8-2 mm (%) \Leftrightarrow \searrow AFP, \searrow gas diffusivity, \searrow pore tortuosity, \searrow saturated hydraulic conductivity • Mean weight diameter not correlated to AFP and slightly to EAW
Cannavo & Michel, 2013	Fine peat (0-10 mm) Coarse peat (20-40 mm)	Raw ¹	<ul style="list-style-type: none"> • \searrow Particle size \Leftrightarrow \searrow AFP, \nearrow unsaturated hydraulic conductivity
Fields et al., 2015	Screened pine bark	Raw ¹	<ul style="list-style-type: none"> • \nearrow Particle size \Leftrightarrow \searrow container capacity (curvilinear correlation), \nearrow air space • No difference between material screen at 6.3 and 4 mm regarding all physical properties studied. • Coarse fraction screened from 2 to 12.7 mm have equivalent TP while < 2 mm has a lower • \searrow particle size \Leftrightarrow \nearrow hydraulic conductivity
Durand et al., 2022	White and black peats, wood fiber, coir, pine bark, perlite, green waste compost	Mean particle length	<ul style="list-style-type: none"> • \searrow mean particle length, \nearrow WHC (quadratic relation), \searrow AFP

¹ Distribution into size interval or cumulative distribution is presented, the materials are distinguished by the global PSD curve

Given the contradictory conclusions reported by previous works mainly based on sieving procedures, measurements of PSD determined by DIA and of some physical properties (WHC, in particular) were performed on some raw materials and on particle size fractions derived from these raw materials, with the objectives:

- to analyze and model the changes in physical properties, as function of particle size,
- to assess the relevance of different particle size descriptors (mean length, mean width, and mean weight diameter) to predict WHC of raw materials from WHC values measured and estimated by the model from particle size fractions.

To meet these objectives, the approach chosen was to sieve materials into several particle size fractions, then, for each raw material and fraction generated, to measure the physical properties as well as morphological characteristics of particles by DIA.

Materials and methods

Particle size analysis by dynamic image analysis

Particle size analysis of raw and fractionated materials was conducted with the QicPic dynamic image analyzer (Sympatec GmbH, Germany), allowing to determine particle sizes ranged from 17 μm to 33.8 mm. Length and width of each particle were assessed from the $\text{Feret}_{\text{Max}}$ and $\text{Chord}_{\text{Min}}$ diameters, respectively (Bartley, 2019; Nguyen et al., 2022; Durand et al., 2022; Durand et al., 2023a), described in Figure 1. $\text{Feret}_{\text{Max}}$ is the maximal distance between two parallel tangents of the particle contour. A chord is the maximum straight distance between two points of the particle contour, measured horizontally; the device measures twenty chords by rotating the particle, $\text{Chord}_{\text{Min}}$ is the smallest chord among all measured chords.

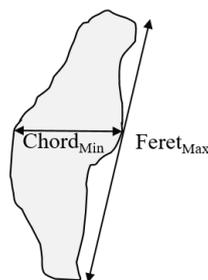


Figure 1. Diameters assessed by DIA: $\text{Feret}_{\text{Max}}$ and $\text{Chord}_{\text{Min}}$, referring respectively to particle length and width.

Measurement procedure was already detailed by Durand et al. (2023a) and are summarized here. DIA is implemented on wet materials previously dispersed in water. Approximately 2 to 3 grams of material were stirred with ~10-15 L water in a tank for 10 minutes, then passed through the QicPic in a constant flow controlled by a peristaltic pump, circulating through the flow cell, placed in front of a camera for continuous image recording. The frame rate was 80 frames per second; two minutes of measurement were conducted per repetition. Three repetitions were carried out, representing 10^7 particles per replicate. The weighting of particle is done according to the projected area of the particles, derived from the diameter of equivalent projection area circle (Figure 1). Raw statistics from the data measured by DIA are provided by the software Paqxos associated to the QicPic device.

Measurement of the physical properties

The water retention properties of the materials were determined using Hyprop devices (Meter, Pullman, USA). Which measures continuously the water potential, with two tensiometers, and the mass moisture content, with a scale, of the material during a free evaporation cycle (Schindler et al., 2015). The materials were prepared as described in the standard NF EN 13041 (AFNOR, 2000), the measurement start close to the saturation of the material (Durand et al., 2023c; *in progress*, Paper 3 of this PhD manuscript). The measurement is conducted in a cylinder of 249 cm³ (5 cm height, 4 cm radius). Data obtained allowed to calculate the TP, AFP, WHC and EAW as proposed by De Boodt & Verdonck (1972), all these values being expressed in volumetric content (%). TP is assessed considering a particle density of 1.55 g.cm³ (Lemaire et al., 1989). WHC and AFP respectively correspond to the volume occupied by water and air at -1 kPa; EAW correspond to the volume of water released between -1 and -5 kPa. In the framework of these measurements, the calculation of the variables is done considering that the volume of the growing media does not evolve during the measurement. However, shrinkage during drying has been observed on these same materials by Durand et al. (2023c; *in progress*, Paper 3 of this PhD manuscript) in the considered water potential ranges. Thus WHC, and AW in water could be slightly underestimated, on the contrary AFP slightly overestimated. Two to four replicates were carried out per sample.

Growing media constituents and particle size fractions studied

This study was carried out from five raw materials representative of the main growing media constituents in the worldwide market (Schmilewski, 2017; Largent & Michel, 2022): white milled *Sphagnum* peat, black *Sphagnum* peat, coir (*Cocos nucifera*), fresh pine bark (*Pinus maritima*), and wood fiber (*Picea* and/or *Abies*). Information about materials are reported in Table 1.

Table 2. Main information about raw materials studied.

Materials	Origin (Supplier ¹)	Extraction / process	PSD raw material ²	Particle size fractions studied					
				mm					
Black peat, H6-H8 ³	DE (FL)	Frozen	0-7	0-0.2	0.2-0.5	0.5-1	1-2	2-8	
Coir	CI (PT)	Grounded	0-25	0-0.2	0.2-0.5	0.5-1	1-2	2-5	5-16
Fresh pine bark	FR (PT)	Screened	0-20	0-0.2	0.2-0.5	0.5-1	1-2	2-5	5-10
White peat, H2-H6 ³	LT (KD)	Milled	0-25	0-0.2	0.2-0.5	0.5-1	1-2	2-5	5-8
Wood fiber	DE (KD)	Defibrated	2-4		0-0.5	0.5-1	1-2	2-5	5-10

1: FL = Floragard Vertiebs-GmbH, KD = Klasmann-Deilmann, PT = Premier Tech Horticulture France

2: Indicated Particle Size Distribution given by the suppliers

3: Von Post degree of humification of *Sphagnum* peats

Each raw material was sieved to obtain various particle size fractions. Choice of size intervals was based on literature review (Handreck, 1983; Verdonck & Demeyer, 2004) and the abundance of each fraction size within the raw materials. The sieving procedure is detailed in Durand et al. (2023a), and is inspired by the standard EN 15428 (AFNOR, 2007). However, in contrast with this latter, materials were sieved at the water content as conditioned in bags for use in culture, instead of a mass moisture content below 15%, in order to avoid risks of hydrophobicity (Michel, 2015). Also, the

materials retained on each sieve were washed with a shower head above the sieve column for facilitating the particle segregation sometimes aggregated (Robertson, 1984; ISO, 1988) and their collection. The resulting cumulative particle width ($\text{Chord}_{\text{Min}}$) and length ($\text{Feret}_{\text{Max}}$) distributions measured by DIA are presented Figure 1.

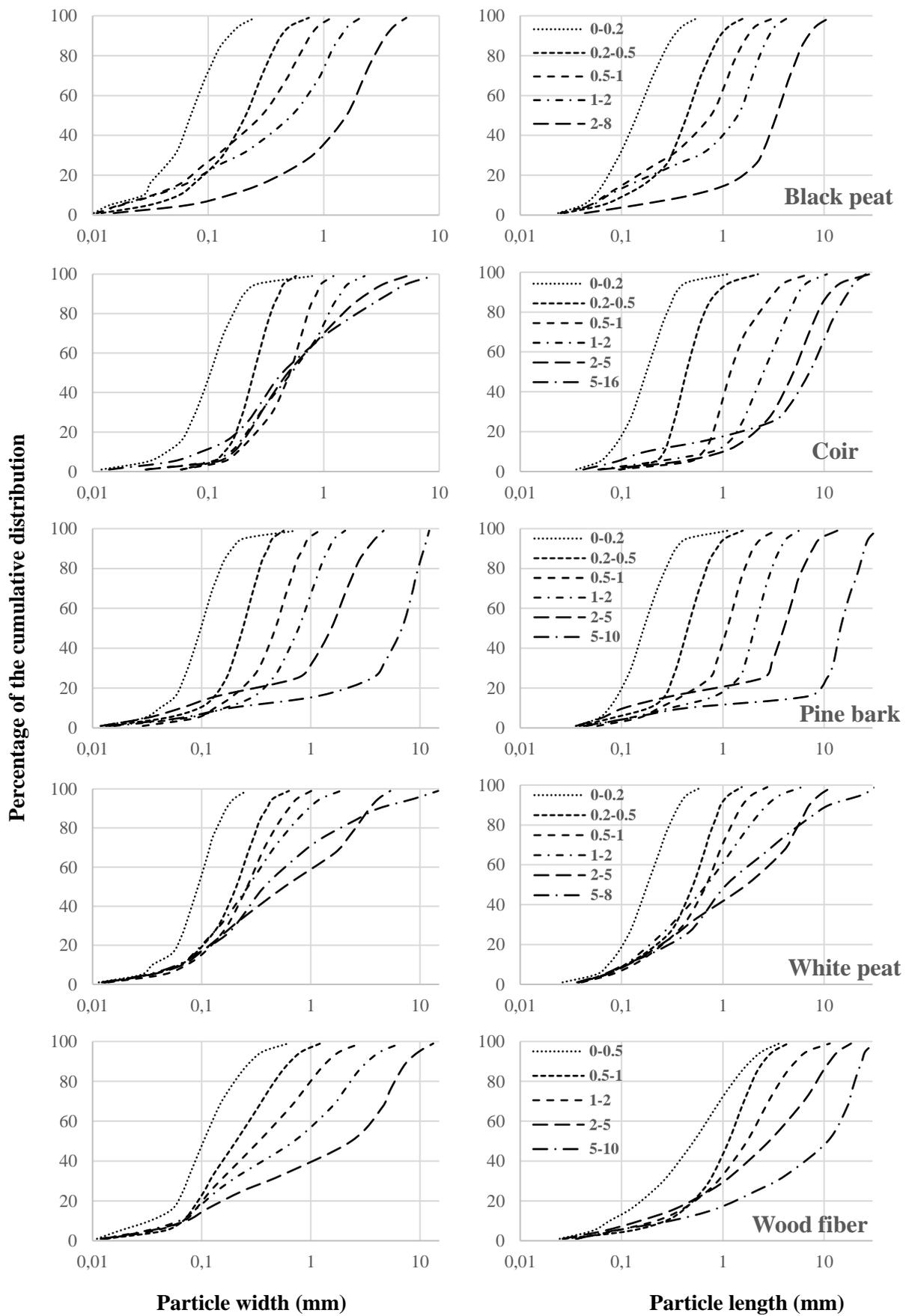


Figure 2. Cumulative particle width ($Chord_{Min}$) and length ($Feret_{Max}$) distributions of the various particle size fraction (in mm) generated by sieving.

Parameters and modeling approach used for analyzing relationships between particle size and physical properties.

Mean particle length and width were used as indicators of PSD determined by DIA, as suggested by Durand et al. (2023a). The arithmetic mean weight diameter (Kemper & Rosenau, 1986; Caron et al., 2005), also called sieve size, derived from the sieving procedure used for fractioning raw materials, was also calculated for each raw material and fraction. The apertures of the sieves composing the set used to calculate this variable was the following, in millimeters: 0.2, 0.5, 1, 2, 4, 5, 8, 10, 16.

According to the previous literature focused on relationships between PSD and physical properties, WHC was selected as indicator describing physical properties measured using the Hyprop systems (WHC showing high correlations with AFP).

For a given material, relationships between particle size parameters (*i.e.*, mean particle length, mean particle width, mean weight diameter) and WHC measured on all particle size fractions were then fitted using similar equation as that used in the Van Genuchten model to describe water potential vs water content relationships (1980). This equation was expressed as follows:

$$WHC_L = WHC_{min} + \frac{WHC_{max} - WHC_{min}}{(1 + |\alpha \cdot L^n|)^m} \quad (Eq. 1)$$

where WHC_L is the water holding capacity for a mean particle length L , WHC_{min} is the minimum water holding capacity and WHC_{max} is the maximum water holding capacity for a given material. α , n and m are parameters without physical meaning describing the shape of the function; m is usually fixed as $m=1-1/n$.

From the fitted curves established for each particle size parameters, root mean square error (RMSE), r^2 , as well as absolute and relative errors between measured and predicted WHC for the raw material were calculated as indicators of the ability of each particle size parameter to predict the WHC.

Results

Physical properties of raw materials

Before analyzing physical properties of size fractions for each material, it should be reported beforehand that the raw materials showed very different water and air retention properties. As commonly observed for most of organic growing media constituents, total porosity was very high for all of them (varying between 89% vol. to 95% vol.), but black and white peats showed high WHC (77% and 75% vol., respectively) and EAW (32% and 30% vol.), and a low AFP (12% and 17% vol.), whereas in contrast, wood fiber and coir exhibited a high AFP (69% and 65% vol., respectively), and low WHC (26% and 31% vol.) and EAW (12% and 16% vol.); pine bark presenting intermediate retention properties (Table 3). These results agree with the abundant literature reported on that topic (De Boodt et al., 1972; Michel, 2010; Caron & Michel, 2021).

Table 3. Particle size (mean length, $Feret_{Max}$; mean width, $Chord_{Min}$; mean weight diameter, MWD) and physical properties of raw materials and derived particle size fractions.

Materials	Particle size fractions	Mean particle length	Mean particle width	Mean Weight Diameter	TP	AFP ¹	WHC ¹	EAW ¹
Black peat	0 - 0.2	0.17	0.08	0.10	90	10	80	19
	0.2 - 0.5	0.51	0.23	0.35	92	18	74	40
	0.5 - 1	0.85	0.35	0.75	92	23	69	36
	1 - 2	1.42	0.64	1.50	91	55	36	9
	2 - 8	3.70	1.69	5.0	90	56	34	7
	Raw	0.64	0.33	1.09	89	12	77	32
Coir	0 - 0.2	0.22	0.13	0.10	92	7	85	16
	0.2 - 0.5	0.54	0.27	0.35	93	11	82	47
	0.5 - 1	1.71	0.52	0.75	94	56	38	13
	1 - 2	3.02	0.68	1.50	95	72	23	5
	2- 5	6.01	0.94	3.50	96	79	17	5
	5 - 16	8.14	1.26	10.5	97	88	9	2
Raw	1.81	0.28	3.77	96	65	31	16	
Fresh pine bark	0 - 0.2	0.21	0.12	0.10	87	9	78	19
	0.2 - 0.5	0.51	0.25	0.35	84	6	78	55
	0.5 - 1	1.16	0.49	0.75	87	54	33	14
	1 - 2	2.15	0.81	1.50	89	63	26	12
	2- 5	4.14	1.63	3.50	90	68	22	8
	5 - 10	14.70	6.27	7.50	92	72	20	7
Raw	1.00	0.47	1.63	86	37	49	19	
White milled peat	0 - 0.2	0.21	0.10	0.10	90	10	80	14
	0.2 - 0.5	0.54	0.22	0.35	94	15	79	30
	0.5 - 1	0.79	0.31	0.75	95	19	76	41
	1 - 2	1.14	0.40	1.50	95	32	63	26
	2- 5	2.93	1.27	3.50	94	37	57	19
	5 - 8	4.09	1.56	6.50	94	45	49	12
Raw	0.56	0.23	1.89	92	17	75	30	
Wood fiber	0 - 0.5	0.78	0.14	0.25	95	37	58	38
	0.5 - 1	1.31	0.30	0.75	96	55	41	26
	1 - 2	2.36	0.58	1.50	96	64	32	16
	2 - 5	4.52	1.29	3.50	96	74	22	10
	5 - 10	11.33	3.23	6.50	95	76	19	8
Raw	1.86	0.47	1.87	95	69	26	12	

¹ AFP and WHC determined at -1 kPa; EAW determined between -1 and -5 kPa

Evolution of physical properties as a function of particle size fractions

For each material, no significant correlation between TP and particle size fractions were observed (Table 3). However, the finer particle size fractions showed lower TP, except for bark where the lowest value was noted for the 0.2-0.5 mm fraction due the high content of sand present in this specific particle size fraction. For coir and bark, higher TPs were reported for the coarser fractions, and

conversely for intermediate particle size fractions for peats and wood fiber. These observations have been detailed by Durand et al. (2023c, *in progress*, Paper 3 of this PhD manuscript) describing in depth the shrinkage curves and the particle arrangement of these particle size fractions.

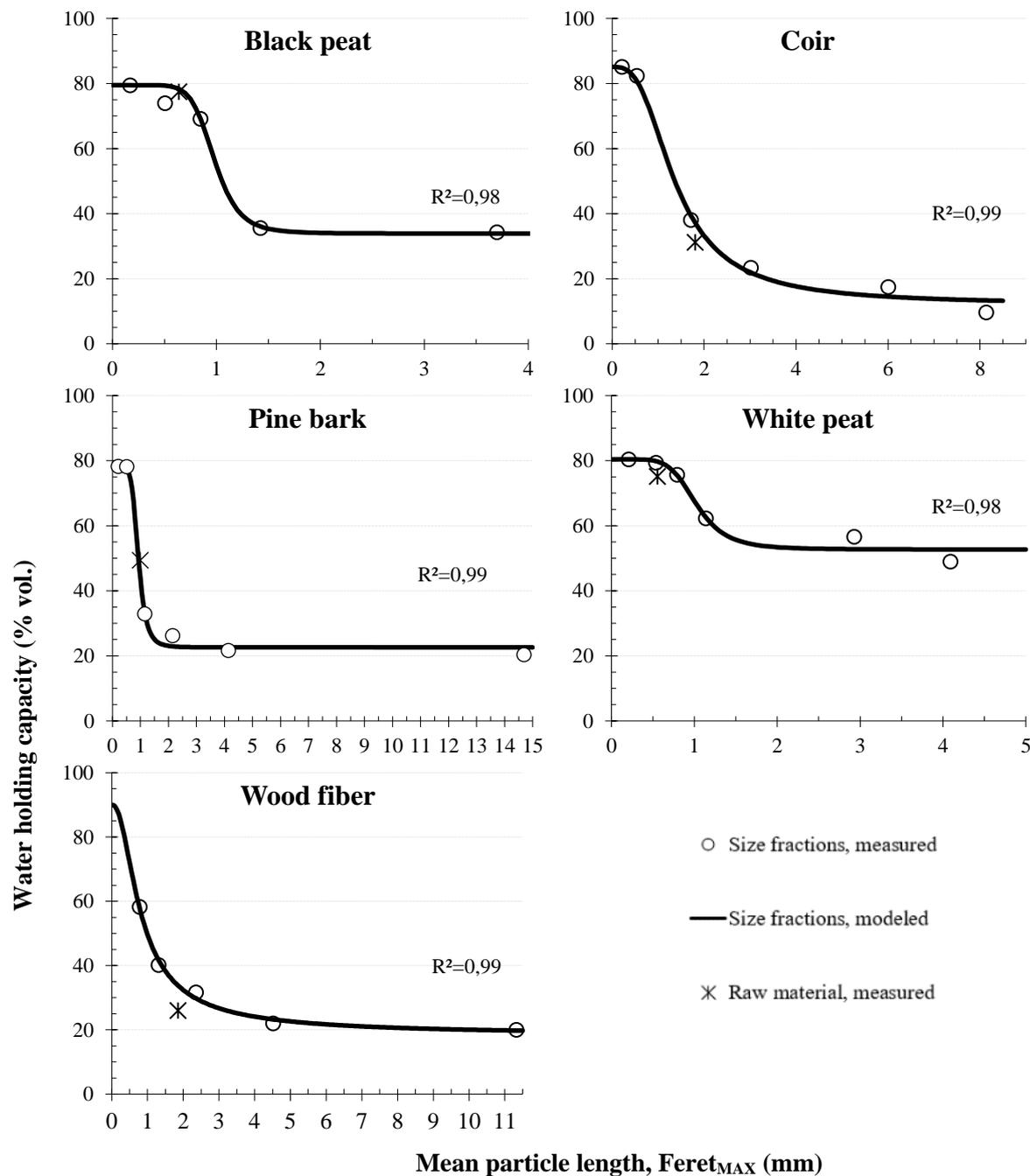


Figure 3. WHC (%) as function of mean particle length for particle size fractions and raw materials.

For peats, bark, and coir, no relationship was observed between EAW and particle size fractions (Table 3), but a same tendency can be reported. The highest EAW were observed in the 0.2-0.5 mm particle size fractions for coir, pine bark, and black peat, and in the 0.5-1 mm particle size fraction for white peat, suggesting that water is strongly retained in the finest fractions, and thus a little bit less available. In contrast, for coarser particle size fractions that those beforehand reported, EAW highly decreased with the increasing particle size fractions. These evolutions in EAW observed for peats, bark and coir can be extended to wood fiber, although this latter showed, in contrast with the

others, a general decrease in EAW with an increase in particle size. However, due to the very low content in the 0.2-0.5 mm particles, this size fraction could not be collected, and the finest fraction for wood fiber was represented by the < 0.5 mm size fraction, probably explaining its higher EAW and the progressive decrease in EAW as a function of increasing particle size fractions.

As usually reported in the literature (Table 1), the smaller the particle size, the higher the WHC, and conversely the lower the AFP for all materials tested (Table 3). WHC and AFP being strongly and inversely correlated ($r = 0.99$, $p\text{-val} = 10^{-30}$), Figure 3 only detailed the changes in WHC as a function of particle size fractions, expressed in terms of mean particle length (Feret_{MAX}). The model used was highly fitted to the data and providing some insight to the relationship between WHC and mean particle length (Figure 3), indicated that WHC strongly decreased in the range of finest particles (*i.e.*, mean particle length lower than 1.25 mm for peats, 1.5 mm for bark and wood fiber, and 2.5 mm for coir), then showed lower decreases in WHC (coir and wood fiber) or reached a plateau (bark and peats) for coarser particle size fractions (*i.e.*, longer mean particle length). Thus, WHC of 60% vol. were approximately reached for mean length particles not exceeding 0.75 mm for wood fiber, 0.85 mm for bark, 0.95 mm for black peat, and 1.15 mm for coir and white peat. Note that the lack of very fine particle size fraction for wood fiber (< 0.2 and 0.2-0.5 mm being merged in a single fraction) probably leads to an inaccuracy for the regression model in this range for small mean particle length.

Predicting water holding capacity of raw materials from particle size fractions

Not only was the relationship between WHC and mean particle length described from particle size fractions for each material, Equation 1 also highly fit those of WHC with mean particle width and with mean weight diameter, as suggested by the low RMSE values (Table 4).

Table 4. Measured and estimated water holding capacity (WHC, % vol.) from mean size (mm), calculated from Equation 1, with root mean square error (RMSE), relative error (as an absolute value) and relative error (%).

Size descriptor		Black peat	Coir	Pine bark	White peat	Wood fiber	Mean errors values
	Measured WHC	77.5	31.2	49.4	75.2	26.0	
Mean particle length (Feret _{MAX})	Mean size	0.64	1.81	1.00	0.56	1.86	
	RMSE	2.89	2.93	1.73	2.86	0.73	2.23
	Estimated WHC	78.4	37.0	43.3	79.7	33.7	
	Relative error	1.2	18.6	12.3	5.9	29.6	13.5
	Absolute error	0.9	5.8	6.1	4.5	7.7	5.0
Mean particle width (Chord _{MIN})	Mean size	0.33	0.28	0.47	0.23	0.47	
	RMSE	2.39	1.84	1.68	2.94	0.42	1.85
	Estimated WHC	72.1	79.6	35.7	80.1	32.9	
	Relative error	7.0	155.1	27.7	6.5	26.5	44.6
	Absolute error	5.4	48.4	13.7	4.9	6.9	15.9
Mean Weight Diameter (sieve size)	Mean size	1.09	3.78	1.63	1.89	1.87	
	RMSE	2.96	6.73	1.82	1.49	0.30	2.66
	Estimated WHC	44.4	15.6	22.8	60.8	29.0	
	Relative error	42.7	50.0	53.8	19.1	11.5	35.4
	Absolute error	33.1	15.6	26.6	14.4	3.0	18.5

From the WHC fitting curves established as function of each of the three size parameters and obtained from particle size fractions, comparisons between measured and estimated WHC values for the raw materials were performed (Table 4). Except for wood fiber, mean particle length always gave the best estimation, with a mean absolute error of 5 (% vol.). In contrast, mean particle width and even other sieve size (*i.e.*, mean weight diameter), mean absolute errors were 15.9% and 18.5%, respectively.

Discussion

Among all the size descriptors, mean particle length (estimated via $Feret_{MAX}$) provided the best fit for predicting WHC (and thus AFP). This result is in line with conclusions reported by Durand et al. (2023), defining mean particle length as one of the most relevant parameters for describing their morphology. Indeed, Igathinathane et al. (2009) and Durand et al. (2023b) reported that mean particle width (assessed *via* $Chord_{Min}$) is less relevant and discriminating than mean particle length to efficiently characterize the particle size fractions. Then, statistic accuracy of sieving is limited by the number of sieves used (Blott & Pye, 2001; Igathinathane et al. 2009).

As previously noted, sieving is less capable to separate non-spherical particles (Igathinathane et al., 2009; Gil et al., 2014; Bartley et al., 2022; Durand et al., 2023a), which is precisely the case for many growing media constituents (Bartley, 2019; Durand et al., 2023b). This was confirmed in Figure 1, showing that the particle width distribution (*i.e.*, the theoretical dimension for separating particles by sieving (Ulusoy & Igathinathane, 2016)) for each particle size fraction was not restricted to the range defining the size fraction. Although weighing the distribution by projected area results in less weight being given to coarse particles than when weighted by volume (Bartley, 2019; Durand et al., 2023a), the mean particle size often being below the lower limit defining the fraction. This may be due to the systemic presence of particles finer than the lower limit of the interval. As a consequence, the mean weight diameter usually overestimates the mean particle size.

However, our results also demonstrated that the larger the width/length ratio, the greater the error on the WHC estimation for raw materials, for wood fiber in particular. The assumption is that the length of elongated particles could be underestimated using $Feret_{MAX}$, which does not consider particle curvature. Although the real length of fiber could be measured by QicPic device, this indicator is conversely not suitable for non-fibrous particles (Durand et al., 2023a).

Compliance of results with the state of the art and new advances

Our hypothesis, that water is strongly retained in the finest fractions (< 0.5 mm for white peat and < 0.2 mm for the other materials tested), and thus less available, could explain the contradictory results about the observed (Abad et al., 2005; Verdonck & Demeyer, 2004) or not (Handreck, 1983; Caron et al., 2005) inverse correlation between EAW and particle size. So that, EAW decreases with an increase particle size when excluding the finest fractions reported above.

Also, this regression model predicted with high confidence and thus seem to agree with relationships between particle size and WHC (and thus AFP), although the proposed model differs with the linear correlation reported by Prasad (2004) and Abad et al. (2005) and with the

quadratic/power regression proposed by Verhagen (1997), both restricted to < 1 mm particles. Our observation is in accordance with previous relationships observed between particle length and WHC on numerous raw growing media constituents using a similar regression model (Durand et al., 2022). Also, our results agree with those reporting changes in AFP and WHC depending on particle size when < 3 mm particles were only considered (Handreck, 1983; Verdonck & Demeyer, 2004), and also with those showing that physical properties do not change (or very little) beyond a certain particle size (Handreck, 1983; Nkongolo & Caron, 1999; Fields et al., 2015). In our case here, beyond values of mean particle length roughly higher than 1.5 mm for peats and bark, and 3 mm for coir and wood fiber. Consequently, our results partially call into question the general conclusion usually reported that the longer the particle length, the higher the AFP and the lower the WHC.

Conclusion

This work detailed an approach in investigating relationships between PSD and physical properties of growing media constituents. This approach is based on PSD analysis using dynamic image analysis of raw materials and the derived particle size distribution, and that of their equilibrium-based physical properties.

The statement that the greater the particle size, the higher the AFP, the lower the WHC was confirmed, but also much more detailed. In contrast, no correlation was found between particle size and water availability. Changes in physical properties mainly occurred for finest particle size fractions (< 1mm for peats and bark, and < 2 mm for coir and wood fiber), in contrast with coarser particle size fractions. These relationships were successfully fitted using regression model, whatever the particle size descriptor used (mean length, mean width, and mean weight diameter). Among them, comparisons between measured and estimated WHC values has allowed to identify mean particle length as the most relevant parameter for predicting WHC.

PSD determination by DIA provides significant advances for the growing media industry to better select raw materials and particle size fractions and to design the next generation of growing media, with the aim to meet the requirements defined in standard procedures (WHC, AFP, EAW, etc.) for static physical properties, and later those for dynamic physical properties (hydraulic conductivity, oxygen diffusivity). Investigations with mixes of constituents should also be developed to check if mean particle length could be also relevant to predict physical properties of mixes, as suggested by results on raw materials which can be considered as a mix of particle size fractions.

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Sum up of the part II

In this second part, the relationships between morphological characteristics (mainly size) and physical properties of growing media were studied.

In a first step, the particle arrangement was studied from shrinkage curves, allowing the identification of a dual pore system: inter-particle (structural) and intra-particle. The results showed that only fine particles present a significant shrinkage in the ranges of water potential for the conduct of irrigation in soilless culture.

In a second step, the physical properties of agronomic interest were studied, according to the particle size determined by image analysis. Among the different descriptors of particle size, the length is the most relevant diameter to make the link with water (and air) retention. The results showed that it is possible to estimate the water retention of raw growing media from regressions obtained on individual fractions.

These results allow a better selection of particles according to their size to control the properties of the growing media.

General conclusion

This general conclusion briefly summarizes the main findings of the work, but largely emphasizes its scientific prospects to develop, and the direct application of this work for the growing media industry.

Main findings

This work has allowed to more precisely characterize the particle morphology (size and shape) of a large diversity of growing media constituents using a new and innovative method, Dynamic Image Analysis, then to evaluate it in order to relate it with some physical properties.

Among the number of particle size and shape descriptors assessed, mean particle length and mean particle circularity were highlighted as more relevant morphological descriptors. These descriptors along with knowing some morphological descriptors are highly correlated to each other, like particle length and elongation have allowed the establishment of a first-order classification of growing media constituents, including diversity, in particle morphology for all raw materials studied.

Relationships between particle morphology and arrangement were then studied from shrinkage curves, such as showing: 1) shrinkage and other static physical properties (water holding capacity, air-filled porosity) depends on particle size, 2) these physical properties can change (such as decreases in WHC and structural shrinkage as well as increase in AFP as particle size increases), 3) these changes were greater in the finest fractions, but less with coarser fractions where changes were quite low. However, a higher specific volume was observed leading to a higher available water, was observed for some materials (peats and wood fiber) for intermediate size fractions. Also, mean particle length has been a responsive measurement to predict physical properties. These measurements demonstrate the utility of DIA tools for characterizing and selecting materials and fractions for designing growing media for tomorrow.

Scientific prospects

This work has led to significant advances in the measurement of particle size and shape of growing media constituents, and began to develop relationships with their static physical properties. In addition, it has brought to light some fields of investigation, which are developed in this last part of this manuscript.

Particle characterization: from a 2-D to a 3-D analysis of particle morphology

This work showed (papers 1 & 2) the benefits to use DIA compared to sieving procedures. It also has identified the limits of each size and shape descriptor to properly describe materials composed of both fibrous and granular particles, which is the case for some growing media constituents. In the same way, DIA tools offer several models to expand particle morphology from 2D to 3D (spherical, ellipsoidal, cylinder models). The model selected by the user is once again more or less adapted for materials presenting a diversity in particle morphology (*e.g.*, mixes of fibers and grains). An in-depth

investigation on materials presenting specific shapes like fibers may allow more accurate characterization of a given material (*e.g.*: length of fiber instead of $Feret_{MAX}$, and 3-D cylinder model instead of 2-D model based on projected area). However, this area will not be primarily addressed (also because that it is unfortunately impossible to segregate and thus select particles from their morphology).

Particle arrangement (structure) & physical properties

The main part of the work was focused on the expanded analysis of particle size and shape, and relationships between particle morphology and physical properties have been restricted so far to equilibrium-based (static) parameters, like water holding capacity (WHC) and air-filled porosity (AFP). Investigations will soon be extended to dynamic parameters, such as unsaturated hydraulic conductivity and gas diffusivity, using approaches reported by Caron et al. (2005) and Nkongolo & Caron (1999), respectively (Figure 1).

<p>Unsaturated hydraulic conductivity is described using the pore-size distribution model of Mualem (1976) combined with the Van Genuchten water retention model (1980), expressed as follows:</p> $K(\psi) = K_s \left(\frac{1 - (\alpha\psi)^{n-2} [1 + (\alpha\psi)^n]^{-m}}{[1 + (\alpha\psi)^n]^{2m}} \right)$ <p>where K_s is the hydraulic conductivity at saturation and α, n and m the fitting parameters coming from the Van Genuchten water retention model.</p>	<p>Gas diffusivity (D_s/D_0) is calculated according to the King & Smith equation (1987):</p> $\frac{D_s}{D_0} = \frac{AFP}{\tau}$ <p>where AFP is the air-filled porosity, D_s is the gas diffusion coefficient within the media ($cm^2 s^{-1}$), D_0 is the gas diffusion coefficient in air ($cm^2 s^{-1}$), and τ is the pore tortuosity of material and is calculated as follows:</p> $\tau = \frac{0.00028\rho g}{\eta K_s} \int_{\theta_r}^{\theta_{ea}} \alpha^2 (\Theta^{-1/b} - 1)^{-2/n} d\theta$ <p>where η is the viscosity of water (in Pa.s), ρ is the density of the water ($g cm^{-3}$), g is the gravity acceleration ($m s^{-2}$), K_s is the saturated hydraulic conductivity ($m s^{-1}$), θ_{ea} is the water content at the air entry point ($m^3.m^{-3}$), θ_r is the residual water content obtained ($m^3.m^{-3}$) from the water retention model of Van Genuchten (1980), α, n and m ($=1-1/n$) are fitted parameters obtained from Van Genuchten model, and $\Theta = (\theta - \theta_r) / (\theta_s - \theta_r)$.</p>
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Figure 1. Models used for characterizing unsaturated hydraulic conductivity and gas diffusivity.

In addition to relationships between particle size and flow properties, special attention will be paid to those between pore tortuosity and particle morphology. From that, the assumption that shrinkage (and its components: interpedal, structural, and basic shrinkages) depends on pore tortuosity can also be analyzed. Our conjecture is all these approaches should be first carried out on particle size fractions derived of the five model raw materials chosen (presented Figure 14, in the general introduction), then on the raw materials themselves. The same model approach as that developed in Paper 5 will then be developed to test the hypothesis that both mean particle length and tortuosity could predict physical dynamic properties.

Shrinkage curves seemed to confirm the presence of a dual porosity of peat samples previously reported by Naasz et al. (2008) and Qi et al. (2011). These two categories of pores, structural and plasma porosity (Braudeau et al., 2004), have also been described for the other materials studied:

bark, coir, and wood fiber. Referring to the general issue of this work to link texture, structure, and physical properties, two main questions emerge for each of structural and plasma porosity:

- Results showed that the volume of structural porosity (and in extension the bulk density) measured for particle size fractions was, in some cases (peats, wood fiber), not correlated to particle size, suggesting a worse particle arrangement for intermediate size fractions (Figure 6, Paper 3). Pore tortuosity calculation and flow properties would help to verify this observation, but the reasons why remain unexplained, and should be investigated (with a special focus on particle shape).
- The change from hydrophilic to hydrophobic character observed for many organic raw materials, and for peats in particular, has been described in the same range of water potentials (Michel et al., 2001; Michel, 2015) than those when the emptying of plasma porosity begins. This is also consistent with observations of Naasz et al. (2008) and Qi et al. (2011) reporting a decrease in wettability when the 2nd porosity started drainage. Contact angle measurements (Michel et al., 2001) and hydration efficiency tests (Fields et al., 2014; Durand et al., 2021) on size fractions and raw materials will also be carried out in order to check this hypothesis, and thus identify the minimum water potential/content threshold avoiding risks of hydrophobicity, which alters surface properties (rewetting), but also swelling properties of the structural porosity as well as water retention properties (Michel et al., 2004; Qi et al., 2011). In any case, questions about the causes explaining the change from hydrophilicity to hydrophobicity still remain: the main hypothesis of a change in molecules conformation at the particle surface (where non-polar molecules replace polar molecules at the particle surface during drying) could maybe explained the basic shrinkage observed for the plasma porosity.

Changes in particle morphology due to biodegradation

As mentioned in the general introduction, the growing media industry is looking for sustainable peat alternatives (Blok et al., 2021). Most of them are organic materials (bark, wood fiber, coir, composts, etc.) with various biological stabilities, and their biodegradation can affect their characteristics (Verhagen, 2009; Domeño et al., 2011), and consequently those of the root environment and plant growth.

The use of DIA should allow to analyze how particle size and shape change during biodegradation, and (in the same approach developed in this work) what are the consequences in terms of particle arrangement (via shrinkage curves) and of physical properties caused by biodegradation. By this way, this work axis should also allow to analyze relationships between biochemical composition and particle size, as well as changes in own intrinsic properties of materials during biodegradation (*e.g.*, potential hydrophobicity). In the longer term, a mechanist model could be developed to predict the changes in particle arrangement and physical properties in relation to particle morphology (size and shape) and its biodegradability.

Refining mixing laws

The following step will be to refine mixing laws and practices. This work and the previous prospects mentioned before, are focused on properties, agronomic quality, and selection of

sustainable raw materials that can be used as peat alternatives. It is therefore necessary to extend this work to mixes of growing media constituents. This step is absolutely essential and much awaited by the growing media industry in order to understand and predict the physical behavior of mixes.

However, this work has already given some information on this purpose. Indeed, raw materials studied can be considered as a mix of derived size fractions, and the proposed regression model has shown that WHC of raw materials have been quite well estimated from their own mean particle lengths. Of course, these good fittings have been developed from size fractions derived from a same raw material, but investigations should be extended to analyze if mean particle length measured on mixes of different growing media constituents (starting with binary mixes) can also be considered as relevant parameter to predict some physical properties. More, as suggested in previous prospects, it could be expected to combine pore tortuosity (as indicator of structure) with mean particle length (as that of texture) to fit static and dynamic physical properties.

Industrial applications

The results of this work are of great interest for growing media companies (as proven by the involvement of some national and international companies in this project), who are looking for sustainable peat alternatives to design their growing media for tomorrow without compromising the agronomic quality of the growing media and that of their plant production.

Results provide key-information (mean particle length in particular) for a better selection and design of particles according to the physical properties required. Results reports the absence of simple correlations between particle size and the other parameters, and also shows that changes largely occur in the range of finest size fractions, in contrast with the coarser ones where differences are quite low. However, these statements have to be qualified since the physical properties largely depend on the nature of the material.

Some specific particle size fractions of peat alternatives meet the recommendations in terms of static physical properties as defined by De Boodt & Verdonck (1972) (*e.g.*, coir, for a mean particle length of 1 mm, corresponding to equivalent sieve size between 0.2-0.5 mm and 0.5-1 mm), suggesting that a more faceted-laced process of raw materials can help to replace peat in the composition of growing media.

The accuracy of DIA, its fast and easy use, and the relevance of mean particular length to describe each material and estimated their physical properties, makes this tool very compelling to use in the selection of raw materials and fractions, but also in the optimization of manufacturing processes (sieving, grinding, etc.) in order to calibrate raw materials towards a desired mean size (or rather, a desired mean particle length). DIA can also be used in quality control for materials, or even more, a standardized procedure could be envisaged for particle size analysis by this tool.

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Titre : Taille et forme des particules des constituants des supports de culture horticoles. Relations avec leurs propriétés physiques.

Mots clés : Analyse d'images, morphologie des particules, substrats horticoles.

Résumé : En culture hors-sol, une gestion raisonnée de l'eau est nécessaire pour augmenter le rendement d'une culture. Les propriétés de rétention en eau et en air des substrats horticoles sont étroitement liées à la morphologie des particules, elle conditionne leur arrangement duquel se dessine un espace poral composant au moins 85% du volume. La morphologie détaillée des particules n'a jamais été réellement étudié pour les substrats horticoles, en partie parce que l'analyse est complexe, en raison de la grande diversité des tailles et des formes des particules. Seul le tamisage a été utilisé pour caractériser les particules, cependant cette méthode rencontre beaucoup de limites (imprécise, peu informative, pas adaptée à toutes formes de particules). Pour détailler les liens entre propriétés physiques et morphologie des particules, les recherches présentées reposent sur l'utilisation de l'analyse d'images dynamique, offrant des résultats plus

précis et détaillés. Diverses mesures de répartitions granulométriques et de propriétés physiques sur une grande diversité de matériaux, ont été effectuées. Les résultats révèlent une très grande diversité des tailles et des formes des particules au sein de chaque matériau. La morphologie des particules peut être résumée par leur circularité et leur longueur. Plus la taille des particules est petite, plus le substrat est composé de pores fins, plus retient d'eau, et inversement moins d'air. Aussi l'évolution de la structure du matériau est impactée par les particules fines. Finalement, la longueur moyenne des particules est un bon estimateur de ses propriétés physiques. Ces travaux donnent des clés aux fabricants de supports de culture pour mieux designer leurs matières et encouragent à caractériser les propriétés physiques par l'étude de la morphologie des particules.

Title: Particle size and shape of growing media constituents. Relationships with their physical properties.

Keywords: Image analysis, particle morphology, horticultural substrates.

Abstract: In soilless culture, a wise management of water is necessary to increase the yield of a crop. The water and air retention properties of horticultural substrates are closely linked to the morphology of the particles, which determines their arrangement and from which a pore space is formed that makes up at least 85% of the volume. The detailed morphology of the particles has never been really studied for growing media, partly because the analysis is complex, due to the great diversity of particle sizes and shapes. Only sieving has been used to characterize the particles, however this method has many limitations (inaccurate, not very informative, not adapted to all particle shapes). In order to detail the links between physical properties and particle morphology, the presented research relies on the use of dynamic image analysis, offering more precise and

detailed results. Various measurements of particle size distributions and physical properties on a wide variety of materials have been performed. The results reveal a very large diversity of particle size and shape within each material. The morphology of the particles can be summarized by their circularity and length. The smaller the particle size, the more fine pores the growing media has, the more water it retains, and conversely the less air. Also, the evolution of the material structure is impacted by finer particles. Finally, the mean length of the particles is a good estimator of its physical properties. This work gives growing media manufacturers keys to better design their materials, and encourages to characterize the physical properties by studying particle morphology.