Effect of sieved fractionation on the physical, flow and hydration properties of *Boscia senegalensis* Lam., *Dichostachys glomerata* Forssk. and *Hibiscus sabdariffa* L. powders

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Abstract This study aimed at evaluating the effect of successive grinding and sieving processes on the physico-chemical properties of powders obtained from *Boscia senegalensis* seeds, *Dichostachys glomerata* fruits and *Hibiscus sabdariffa* calyxes. Plant powders were fractionated into four granulometric classes and their properties were compared to those of unsieved powders. Mean particle size exerted a significant influence ($p < 0.05$) on the plant powders properties. The smaller the particle size of the powder fraction, the higher the protein, lipid and ash contents and the lower the carbohydrate and fiber contents. The decrease in particle size increased particle sphericity and elongation and enhanced flowability of *B. senegalensis*

and *D. glomerata* powders, whereas an inverse tendency seemed to be observed for *H. sabdariffa* powders. Water absorption capacity, water solubility index and dispersibility were improved for finer particles for all plants. Sieve fractionation is a novel approach for improving physicochemical properties of plant powders.

Keywords Plant powders · Sieve fractionation · Particle size distribution · Shape factors · Powder flowability · Hydration properties

Introduction

Nowadays, plant-derived bioactive products have gained interest owing to their numerous health and nutritional benefits. Powdered materials are preferably used as ingredients in various industry such as foods, pharmaceutical and cosmetics (Leuenberger and Lanz, 2005). In fact, most of current food ingredients and pharmaceutical excipients are commonly manufactured in powder form (Jan et al., 2017). Another advantage of powder technology resides in the convenience offered by powdered products, especially regarding higher shelf-life and easier transportability (Forny et al., 2010). In addition, the substitution of the conventional extraction methods of bioactive ingredients from plants using solvents is required for environmental and safety reasons. So, it becomes imperative to use modern sustainable technologies to develop food supplements from natural sources (Qi et al., 2015; Karam et al., 2016).

Controlled Differential Sieving process (CDS_p) is an emerging technology showing great potential in the production of food powders with outstanding functional properties (Baudelaire, 2013). This process encompasses

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different processes including drying, fine grinding and sieving, and it leads to the production of solid particles ranging from 20 to 500 µm from plant parts. It is worth noting that drying, grinding and sieving are complex processes, whose operating conditions may lead to particle with variable physicochemical and functional characteristics (Baudelaire, 2013; Landillon et al., 2008). In fact, physicochemical properties have a great impact on powder functionalities (hydration, flowability, etc.) and determine the conditions by which they should be used, handled and stored. For example, particle properties of active drug substances play an important role in the manufacturing performance of tablet production and dosage form. Many properties like particle size distribution, particle shape, morphology, roughness, density, cohesiveness, compressibility, water solubility, wettability, surface interactions and hygroscopicity are crucial for successful drug design and development (Rasanen et al., 2003). However, powder characteristics are closely related to particle size and thus to process conditions used for their production (Meghwal and Goswami, 2014). Therefore, it is of great importance to determine the physical, flow and hydration characteristics of food powders in order to use them efficiently as functional food ingredients (Benković et al., 2017) and predict powder behavior during rehydration processes (Molenda and Stasiak, 2002; Sharma and Joshi, 2007).

Studies have been conducted to understand the influence of particle size on powder physical and flow properties (Maeda et al., 2017; Siliveru et al., 2017). However, conclusions were rather different depending on the intrinsic properties of plant materials such as surface properties (Petit et al., 2017; Szulc and Lenart, 2016), granulometric and shape properties of produced powder (mean particle size, with of particle size distribution, shape and surface roughness) and process conditions employed during powder production (Kim et al., 2009). For instance, Singh and Prasad (2013) reported an increase in aerated bulk density with particle size for *Moringa oleifera* leaf powders, while Sharma et al. (2013) observed an opposite trend for mango pulp powders. Moreover, Siliveru et al. (2017) evidenced that powders from different plants but having the same mean particle size generally differ in terms of physical properties and flow behavior.

Boscia senegalensis, *D. glomerata* and *H. sabdariffa* are tropical and subtropical plants extremely attractive for food and medicinal usages. Their biological properties have been reported in previous studies (Da-Costa-Rocha et al., 2014; Abdou Bouba et al., 2010; Dongmo et al., 2017) and powders from *Boscia senegalensis* seeds, *Dichostachys glomerata* fruits and *Hibiscus sabdariffa* calyxes may constitute good sources of natural antioxidants that can be used as functional food ingredients and nutraceuticals. *Boscia senegalensis* is a plant of the Cappariaceae family. Its

seeds are widely consumed and represent an important food source (famine food) in most of the developing countries. The presence of antioxidant compounds makes seeds of this plant a valuable source of functional components (Dongmo et al., 2017).

Likewise, *D. glomerata*, belonging to the Mimosaceae family, has been reported to possess a wide range of bioactive compounds (Abdou Bouba et al., 2010). Dry fruit pods are commonly used as spices in a traditional soup in Cameroon (Tchiegang and Mbougung, 2005). Beneficial properties include antioxidant, anti-inflammatory, antihypertensive, anti-cancer and anti-diabetic effects (Fankam et al., 2011; Kuate et al., 2013). *D. glomerata* fruit powder has been used as supplement for enhancing growth performance of farmed chicken and producing chicken meat free from antibiotics residues (Kana et al., 2017).

Last, *H. sabdariffa* is an herbaceous plant widely cultivated in tropical and subtropical areas (Sinela et al., 2017). Nutritional importance of their calyxes is mainly due to the high content in anthocyanins and other bioactive compounds (Borrás-Linares et al., 2015). Calyxes are used as food coloring in numerous industrial applications and for the preparation of a soft drink widely consumed for its various health benefits (Frimpong et al., 2014). Health benefits associated with *H. sabdariffa* calyxes include antihypertensive, anti-inflammatory, antidiabetic, hepatoprotective, antioxidant and antibacterial activities (Peng et al., 2011; Nyamukuru et al., 2017). It has also proved its efficacy in reducing blood pressure of adult patients with non-complicated hypertension when administered in the galenic form of capsules of *H. sabdariffa* powder (Seck et al., 2017).

The objective of the current study was to investigate the potential of powders obtained from *Boscia senegalensis* seeds, *Dichostachys glomerata* fruits and *Hibiscus sabdariffa* calyxes to serve as functional and food ingredients. Hence, the influence of particle size on powder characteristics was investigated by comparing the physicochemical (granulometry, morphology, proximate composition) and functional (hydration and flowability) properties of different granulometric classes of these powders obtained by CDSp. Unsieved powders were also analyzed and served as controls.

Materials and methods

Plant material

Boscia senegalensis seeds, *Dichostachys glomerata* fruits and *Hibiscus sabdariffa* calyxes were employed in this study. Dried fruits of *D. glomerata* and dried red calyxes of *H. sabdariffa* were purchased in May 2015 from local

markets, respectively in the Center and Adamawa regions of Cameroon, whereas dry seeds of *B. senegalensis* were purchased from Batha market in Oum-Madjer state of Chad. *D. glomerata* and *H. sabdariffa* samples were hand-cleaned of foreign bodies (inorganic materials, dirt and dust particles) before been used for powder production. Likewise, the fruits of *B. senegalensis* were manually decorticated and obtained seeds were used for powder production.

Chemicals

Sodium hydroxide (NaOH), hydrochloric acid (HCl), sulfuric acid (H₂SO₄), boric acid (H₃BO₃), chloroform, methanol, ethanol, potassium ferricyanide (K₃Fe(CN)₆), D-glucose, zinc sulfate, aqueous phenol and acetone, sodium phosphate monobasic anhydrous (NaH₂PO₄), sodium phosphate dibasic anhydrous (Na₂HPO₄), α -amylase, amyloglucosidase and protease were obtained from Sigma-Aldrich (Saint-Louis, USA).

Plant grinding

The electric Ultra-Centrifugal Mill ZM 200 (Haan, Germany) supplied with a 24-tooth rotor of 99 mm diameter and a sieve drilled with 1 mm trapezoid holes was employed for grinding dry plant samples. Grinding was operated 100 g batches at 12,000 rpm for 1 min in ambient air (Becker et al., 2016; Zaiter et al., 2016).

Powder sieving

Obtained plant powders were separated into granulometric classes using a series of three selected sieves of various apertures (180, 212 and 315 μ m). The sieves were installed on an Analysette 3 Spartan sieve shaker (Fritsch, Idar-Oberstein, Germany), operating by vertical vibration at 0.5 mm vibration amplitude. For each batch, 100 g powder was gently poured on top sieve and sieving was performed in permanent mode for 10 min. After that, the powder mass retained on each sieve was collected and weighed. This permitted to produce three granulometric classes: < 180 μ m, 180–212 μ m and $\geq$ 315 μ m. Some unsieved powder of each plant was kept to serve as control. Powder samples were packaged in polyethylene bags and stored at 10 °C until analysis.

Proximate composition of plant powders

Moisture content was determined by drying 5 g powder sample in an oven at 103 °C for 24 h until reaching constant weight (AOAC, 1990). Ash content was evaluated by incinerating from 3 to 5 g powder sample placed in crucibles for 12 h at 550 °C according to AOAC method

920.87 (1990). Azote titration was carried out by acid digestion in Kjeldahl tubes (Kjeldatherm, Gerhardt, Les Essarts le Roi, France) at 400 °C followed by distillation and titration (Automatic distillator, Gerhardt) (AOAC method 991.20) and crude proteins were calculated using the classical 6.25 conversion factor (AOAC, 1990). Folch method (1957) was used for total fat quantification and the carbohydrate content was determined according the sulfuric acid method as described by Dubois et al. (1956). Total fiber content was evaluated by the combination of enzymatic and gravimetric methods (AACC, 1999), in which powder samples were gelatinized by heat-stable α -amylase at 95 °C and then enzymatically digested successively with protease and amyloglucosidase at 60 °C. Ethanol was then used to precipitate fibers and the residue was filtrated and washed with ethanol and acetone. After drying, the residue was weighed and its ash and protein contents were determined as previously described. Content in total fiber was then calculated as the weight ratio between residue and powder sample, minus ash and protein contents of the residue.

Physical properties of plant powders

Particle size analysis

The particle size distribution was determined using laser by Mastersizer 3000 (Malvern Instruments, Orsay, France) supplied with the Aero S dry dispersion unit. Feed rate and pressure were adjusted to reach a laser obscuration level of circa 2%: 2.5 mm hopper length, 30% feed rate for *Dichrostachys glomerata* and *Hibiscus sabdariffa* powders and 70% feed rate for *Boscia senegalensis* powders. The chosen size estimator was the particle size in volume and classical granulometric parameters were determined: D10, D50 and D90; where DX means that 10, 50 and 90% of sample particles had diameters inferior to DX. The width of particle size distribution was evaluated through the span (dimensionless), calculated as follows (Eq. 1):

$$\text{Span} = \frac{D90 - D10}{D50} \quad (1)$$

Water activity

Water activity was evaluated at 20.0 ± 1.5 °C with an a_w -meter instrument (R tonic Hygropalm) measuring the variation of water partial pressure. 15 g powder were poured into a measurement vessel and the AW-Quick method was employed, leading to water activity stabilization in about 4–5 min.

Colorimetry

Powder color was characterized using a colorimeter (Datacolor International Microflash 2078S, Montreuil, France). Powders were placed in a Petri dish. The colorimeter was previously calibrated with a standard calibration plate having white and black areas. The CIEL*a*b* color system was employed for color characterization. Reported values correspond to the average of six measurements performed at different locations of the powder layer. Results were expressed in the CIEL*a*b* color system in accordance with (Manickavasagan et al., 2015). L^* corresponds to the lightness coordinate ranging from no reflection for black ($L^* = 0$) to perfect diffuse reflection for white ($L^* = 100$), a^* is the redness coordinate varying from negative values for green to positive values for red and b^* is the yellowness coordinate ranging from negative values for blue and positive values for yellow. Hue angle (H^*) and chromaticity (C^*) values were also calculated as follows:

$$H^* = \arctan\left(\frac{b^*}{a^*}\right) \quad (2)$$

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (3)$$

Particle shape analysis

Particle shape characteristics were determined by dynamic image analysis with a QICPIC morphogranulometer (Sympatec GmbH, Clausthal-Zellerfeld, Germany) equipped with a dry sample disperser VIBRITM (Sympatec GmbH) and Windox 5.4.2007 software according to method used by Gaiani et al. (2011). Approximately 5 g of powder was filled into the high-speed sample disperser, where it was accelerated up to 100 m/s at 1.5 bars by a Venturi tube. Dispersion of powder particles aimed at avoiding particle superimposition on acquired images. The image analysis evaluation was based on the equivalent projection area of a circle (EQPC), defined as the diameter of a circle that has the same area as the projection of the particle, which was chosen as size estimator. The sphericity and convexity were determined from EQPC. The sphericity of particles was calculated from particle images as the ratio between the EQPC perimeter and the real perimeter of a particle, leading to values ranging from 0 to 1. The sphericity is defined as the ratio between the perimeter of an equivalent circle with the same project area as actual particle and the real particle, so any increase in particle perimeter without changing its projected area would lead to a decrease in sphericity. The smaller sphericity value, the more irregular the particles shape. Convexity is defined as the ratio of the projection area itself and the area of the

convex. Without concave regions, the maximum theoretical convexity is 1.

Flow properties of plant powders

Flow characteristics of powder samples were evaluated with the FT4 powder Rheometer (Freeman Technology, Malvern). This equipment possesses the advantage to automate the test procedure, thus requiring minimal operator intervention. Stability, compressibility and shear cell tests were performed to assess powder flowability in low-stress environment, compressibility under normal stress and powder flowability in high-stress environment, respectively.

Stability test

Flow energy (Basic flowability energy, BFE (mJ)) is used to evaluate the flow properties of powders under free-surface conditions. The powder was placed in a cylindrical vessel (25 mm × 25 mL split vessel) and underwent a conditioning step at 100 mm s⁻¹ blade tip speed. Then, seven test cycles (conditioning + test) were performed to achieve stabilized flow energy. The flow energy was calculated from the work of normal force and torque of the blade when moving downward through the powder bed. BFE, corresponding to the stabilized flow energy, was evaluated as the energy needed to displace a conditioned powder sample during downward movement of the blade in the seventh test cycle (Freeman, 2007). The Conditioned bulk density (CBD) was also obtained in the stability test: it was calculated as the ratio of sample mass to vessel volume (25 mL).

Shear cell test

Shear cell test was performed using the rotational shear cell accessory of the FT4 powder rheometer. It consisted of a vessel (25 mm × 10 mL split vessel) containing the sample powder and a shear head to apply both normal stress and rotational shear to the powder bed. Powder sample was first conditioned using the helical blade and then slowly pre-compacted under a determined normal load (9 kPa) with a vented piston (Quintanilla et al., 2001). Then, the vessel containing the powder sample was split, the vented piston was changed for the shear cell head and the powder sample was recompressed to remove any disturbances caused by the split and ensure that the surface of the sample was properly consolidated. After this preconsolidation step, the sample was pre-sheared at 9 kPa to achieve a critically consolidated state. The normal stress σ was then lowered and the shear stress τ necessary to cause powder bed failure

and initiate flow was measured. The pre-shear/shear sequence was repeated five times at decreasing normal stresses σ from 7 to 3 kPa by 1 kPa steps. The curve representing the evolution of τ as a function of σ is thus the so-called yield locus. Shear cell parameters, mainly unconfined yield stress (UYS), major principal stress (MPS), cohesion and flow factor, were then determined by the software by analysis of the Mohr circle. The cohesion is evaluated as the intercept of the linear regression of the shear stress vs. applies normal stress curve, whereas flow factor (ff) is defined as the ratio between MPS and UYS. The larger flow factor coefficient (ffc) is, i.e., the smaller the ratio of the unconfined yield strength to the consolidation stress, the better o bulk solid flows. Similar to the classification used by Jenike (1980), one can define flow behavior as follows: $ffc < 1$ not flowing, $1 < ffc < 2$ very cohesive, $2 < ffc < 4$ cohesive, $4 < ffc < 10$ easy-flowing and $10 < ffc$ free-flowing. Flow indicator such as compressibility (C_p) is calculated from the density values of conditioned bulk density (CBD) and density after compaction at 9 kPa (BD), and is indicative of the cohesion between particles (Eq. 5).

$$C_p(\%) = \left(1 - \frac{CBD}{BD}\right) \times 100 \quad (4)$$

Hydration properties of plant powders

Water absorption capacity and water solubility index

Water absorption capacity (WAC) and water solubility index (WSI) were evaluated according to Mahasukhon-thachat et al. (2010) with slight modifications. 0.35 g plant powder was weighed and loaded into a 50-mL tared graduated centrifuge tube where 10 mL distilled water was added. Then, the mixture was stirred at 300 rpm (Variomag Poly) for 40 min at 20 °C. The solution was then centrifuged (Thermo Scientific, Heraeus Megafuge 8R Centrifuge) at 224 g for 10 min at 20 °C. The supernatant was carefully removed by inverted tubes for 1 min and retained sediments were weighed for the determination of water absorption capacity. The latter was expressed as grams of water bound per gram of sample on dry basis. The collected supernatant was dried in an oven at 103 °C for 4 h, cooled in a desiccator and weighed for evaluation of water solubility index. The WAC and WSI were calculated as follows:

$$WAC(g/g) = \frac{\text{Weight of sediments (g)}}{\text{Dry weight of powder (g)}} \quad (5)$$

$$WSI(\%) = \frac{\text{Dry weight of supernatant (g)}}{\text{Dry weight of powder (g)}} \times 100 \quad (6)$$

Dispersibility

Dispersibility was performed according to Jinapong et al. (2008). Exactly, 1 g powder was suspended in 10 mL distilled water in a 50-mL beaker at 20 °C. The sample was manually mixed for 15 s making 25 complete movements back and forth across the whole diameter of the beaker. The reconstituted powder was then filtrated through a 180- μ m sieve. Powder retained on the sieve was placed in a dried aluminum pan and dried for 4 h in an oven at 105 °C, then weighted. The dispersibility index is the amount of dry matter dispersed in water which can pass through a 180- μ m sieve, expressed as a mass percentage. The dispersibility of the powder was calculated as follows:

$$\text{Dispersibility}(\%) = \frac{[(10 + a) \cdot \%TS]}{[a \cdot (100 - b)]} \times 100 \quad (7)$$

where a mass of powder sample (g), b moisture content of the powder sample and $\%TS$ dry matter of reconstituted powder after sieving (% (w/w)).

Statistical analysis

All results in this work were expressed as mean $\pm$ standard deviation of three replicates. The data were subjected to analysis of variance to determine significant differences with Duncan's multiple range tests at 5% confidence level. The relationship between measured parameters was assessed by Pearson correlation test. Principal Component Analysis (PCA) was used to evaluate the degree of correlation between physical and flow properties.

Results and discussion

Proximate composition of plant powders

The proximate composition analysis of *B. senegalensis*, *D. glomerata* and *H. sabdariffa* powder samples are presented in Table 1. Moisture contents ranged between $4.66 \pm 0.01\%$ (w/w) (*B. senegalensis* unsieved powder) and $8.22 \pm 0.19\%$ (w/w) (*H. sabdariffa* > 315 μ m) on wet basis. Generally, moisture content lower than 10% ensures powder stability during storage (Kaur et al., 2011). Statistical analysis permitted to show that protein, fat and ash contents increased when particle size was decreased, unlike carbohydrates and total fibers which decreased. Previous studies explained that plant parts containing a higher proportion of fibers and sugars are harder to grind and thus

Table 1 Proximate composition (expressed as percentages on dry basis) of *Boscia senegalensis*, *Dichrostachys glomerata* and *Hibiscus sabdariffa* granulometric classes and unsieved powders

	Powder samples	Moisture*	Ash	Protein	Fat	Fiber	Carbohydrates
<i>Boscia senegalensis</i>	< 180 µm	5.77 ± 0.20 ^c	3.63 ± 0.16 ^c	33.16 ± 0.60 ^d	7.63 ± 0.07 ^c	2.32 ± 0.19 ^a	50.47 ± 0.50 ^a
	180–212 µm	4.89 ± 0.19 ^a	3.50 ± 0.34 ^{bc}	31.38 ± 0.50 ^c	7.19 ± 0.21 ^b	3.10 ± 0.22 ^b	52.92 ± 0.16 ^b
	212–315 µm	4.71 ± 0.08 ^a	4.31 ± 0.21 ^d	30.12 ± 0.54 ^b	7.13 ± 0.11 ^b	3.54 ± 0.15 ^c	54.73 ± 1.00 ^b
	> 315 µm	5.33 ± 0.33 ^b	3.17 ± 0.01 ^b	28.92 ± 0.04 ^a	6.57 ± 0.13 ^a	5.25 ± 0.32 ^d	57.09 ± 0.90 ^c
	Unsieved powder	4.66 ± 0.01 ^a	2.24 ± 0.13 ^a	31.72 ± 0.39 ^c	7.15 ± 0.15 ^b	3.28 ± 0.19 ^{bc}	53.67 ± 0.50 ^b
<i>Dichrostachys glomerata</i>	< 180 µm	6.17 ± 0.17 ^a	4.48 ± 0.46 ^c	16.14 ± 0.11 ^b	2.68 ± 0.19 ^a	16.16 ± 0.36 ^a	18.16 ± 0.6 ^a
	180–212 µm	7.33 ± 0.33 ^c	3.96 ± 0.01 ^{ab}	15.93 ± 0.40 ^b	4.22 ± 0.28 ^c	17.76 ± 1.42 ^b	19.01 ± 0.66 ^a
	212–315 µm	6.50 ± 0.17 ^{ab}	4.17 ± 0.09 ^b	15.93 ± 0.30 ^b	3.75 ± 0.25 ^b	20.46 ± 0.66 ^c	23.17 ± 0.67 ^b
	> 315 µm	6.89 ± 0.19 ^b	3.58 ± 0.35 ^a	15.70 ± 0.56 ^b	2.57 ± 0.18 ^a	26.91 ± 0.85 ^d	31.25 ± 0.99 ^c
	Unsieved powder	6.11 ± 0.19 ^a	6.04 ± 0.01 ^d	14.91 ± 0.16 ^a	2.42 ± 0.18 ^a	21.06 ± 0.83 ^c	22.12 ± 0.41 ^b
<i>Hibiscus sabdariffa</i>	< 180 µm	7.00 ± 0.01 ^a	11.47 ± 0.36 ^{bc}	6.93 ± 0.08 ^{ab}	4.30 ± 0.26 ^d	5.78 ± 0.39 ^a	65.25 ± 1.65 ^a
	180–212 µm	8.11 ± 0.38 ^c	10.88 ± 0.05 ^{ab}	6.89 ± 0.12 ^{ab}	2.92 ± 0.19 ^c	8.00 ± 0.44 ^b	67.54 ± 0.42 ^b
	212–315 µm	7.42 ± 0.37 ^{ab}	10.44 ± 0.32 ^a	7.08 ± 0.21 ^b	2.26 ± 0.12 ^b	9.80 ± 0.16 ^c	67.11 ± 0.66 ^b
	> 315 µm	8.22 ± 0.19 ^c	11.62 ± 0.34 ^c	6.74 ± 0.20 ^a	1.46 ± 0.12 ^a	9.88 ± 0.01 ^c	72.51 ± 0.92 ^d
	Unsieved powder	7.83 ± 0.50 ^{bc}	11.03 ± 0.48 ^{abc}	7.00 ± 0.16 ^{ab}	2.39 ± 0.19 ^b	7.94 ± 0.13 ^b	69.41 ± 0.70 ^c

*Expressed as percentages on wet weight. Means ± standard deviations with different superscripted letters within the same column differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

result in larger particles after grinding whereas plant parts with higher levels of minerals, fat and proteins are easier to grind and thus lead to smaller particles (Becker et al., 2016; Zaiter et al., 2016). In fact, cell walls are made of highly complex large biopolymers such as cellulose, hemicellulose, lignin and pectin, which enter in the fiber category. Cellulose, the most abundant carbohydrate polymer in the nature, is the main structural component of plant cell walls, contributes to the rigidity of call walls, making them extremely difficult to grind (Doi and Kosugi, 2004; Flávia et al., 2016).

Physical characteristics of plant powders

Particle size distribution

Particle size distribution of unsieved plant powders of *B. senegalensis*, *D. glomerata* and *H. sabdariffa* were bimodal with a population of fine particles around 20–30 µm and a population of large particles around 300–500 µm. The major population of *D. glomerata* and *H. sabdariffa* unsieved powders corresponded to large particles, whereas fine particles were more numerous for *B. senegalensis* unsieved powder. The presence of two well-defined particle populations in investigated samples is an indication of

the suitability of powders to be fractionated in granulometric classes having markedly different characteristics, especially particle size (Bernhart and Fasina, 2009). These observations were confirmed by granulometric parameters presented in Table 2. First, it can be seen that *D. glomerata* and *H. sabdariffa* had similar characteristics (high D_{50} and moderate span) showing that particles obtained by grinding of these two plants were rather large, in accordance with their relatively high fiber content (21.06 and 7.94% (w/w) on dry basis). The presence of a significant proportion of fine particles in *B. senegalensis* unsieved powder was confirmed by its low D_{50} associated with the elevated span; it can be related to the rather low fiber content (3.28% (w/w) on dry basis, cf. Table 1) of this powder. The sieving procedure was efficient for *D. glomerata* and *H. sabdariffa* powders, as obtained granulometric classes had well different D_{50} and low-to-medium spans of particle size distributions (Table 2). On the contrary, it can be noted from the very low D_{50} values of *B. senegalensis* granulometric classes that fine particles were present in all obtained fractions, which may reflect the tendency of *B. senegalensis* to be cohesive, thus impairing sieving efficiency. Indeed, fine particles can stick to larger particles and thus be retained by sieves of mesh size exceeding their diameter. Moreover, *B. senegalensis* powders were richer in fat than *D. glomerata* and *H. sabdariffa* powders (cf. Table 1),

Table 2 Physical properties of *Boscia senegalensis*, *Dichrostachys glomerata* and *Hibiscus sabdariffa* granulometric classes and unsieved powders

Plants	Powder samples	D ₅₀ (µm)	Span (—)	Water activity a _w (—)	Hue angle (°)	Chromaticity (—)	Convexity (—)	Sphericity (—)
<i>Boscia senegalensis</i>	< 180 µm	35.53 ± 0.06 ^d	4.25 ± 0.06 ^a	0.305 ± 0.004 ^d	87.55 ± 0.65 ^a	16.06 ± 0.65 ^b	0.876 ± 0.002 ^c	0.865 ± 0.009 ^b
	180–212 µm	26.10 ± 0.30 ^b	5.42 ± 0.12 ^b	0.300 ± 0.001 ^c	88.43 ± 0.72 ^{ab}	13.36 ± 0.55 ^a	0.874 ± 0.001 ^b	0.856 ± 0.012 ^b
	212–315 µm	26.63 ± 0.21 ^b	7.13 ± 0.29 ^c	0.257 ± 0.001 ^b	89.60 ± 0.07 ^c	13.88 ± 0.17 ^a	0.845 ± 0.006 ^a	0.824 ± 0.009 ^a
	> 315 µm	24.70 ± 0.10 ^a	10.53 ± 0.10 ^e	0.256 ± 0.001 ^b	88.09 ± 0.43 ^{ab}	13.54 ± 0.59 ^a	0.848 ± 0.007 ^a	0.829 ± 0.012 ^a
	Unsieved powder	28.60 ± 1.01 ^c	8.63 ± 0.36 ^d	0.250 ± 0.002 ^a	88.69 ± 0.55 ^{bc}	13.72 ± 0.43 ^a	0.847 ± 0.006 ^a	0.826 ± 0.008 ^a
<i>Dichrostachys glomerata</i>	< 180 µm	109.33 ± 0.58 ^a	1.89 ± 0.02 ^a	0.248 ± 0.004 ^b	5.50 ± 0.05 ^a	13.50 ± 0.14 ^a	0.905 ± 0.001 ^a	0.830 ± 0.005 ^d
	180–212 µm	115.33 ± 0.58 ^b	2.54 ± 0.05 ^b	0.232 ± 0.002 ^b	5.85 ± 0.23 ^{ab}	14.66 ± 0.38 ^b	0.897 ± 0.003 ^a	0.816 ± 0.002 ^c
	212–315 µm	236.00 ± 2.65 ^d	1.86 ± 0.04 ^a	0.231 ± 0.003 ^b	6.18 ± 0.29 ^{bc}	15.86 ± 0.59 ^c	0.913 ± 0.001 ^b	0.801 ± 0.002 ^a
	> 315 µm	397.33 ± 4.62 ^e	1.87 ± 0.02 ^a	0.232 ± 0.003 ^b	6.27 ± 0.05 ^{bc}	16.02 ± 0.34 ^c	0.926 ± 0.001 ^c	0.814 ± 0.002 ^{bc}
	Unsieved powder	166.33 ± 2.08 ^c	3.09 ± 0.01 ^c	0.207 ± 0.023 ^a	6.48 ± 0.30 ^c	17.15 ± 0.17 ^d	0.910 ± 0.001 ^b	0.810 ± 0.002 ^b
<i>Hibiscus sabdariffa</i>	< 180 µm	46.33 ± 0.51 ^a	3.52 ± 0.05 ^c	0.301 ± 0.001 ^a	6.66 ± 0.13 ^c	20.74 ± 0.05 ^e	0.873 ± 0.001 ^a	0.825 ± 0.002 ^a
	180–212 µm	174.33 ± 2.52 ^c	1.72 ± 0.02 ^b	0.331 ± 0.001 ^d	4.97 ± 0.05 ^b	15.36 ± 0.59 ^c	0.917 ± 0.001 ^c	0.817 ± 0.001 ^a
	212–315 µm	311.67 ± 1.15 ^d	0.95 ± 0.02 ^a	0.322 ± 0.007 ^c	3.60 ± 0.28 ^a	13.79 ± 0.10 ^b	0.936 ± 0.001 ^d	0.822 ± 0.003 ^a
	> 315 µm	507.00 ± 3.00 ^e	0.91 ± 0.01 ^a	0.323 ± 0.003 ^c	3.71 ± 0.28 ^a	13.20 ± 0.12 ^a	0.944 ± 0.001 ^d	0.822 ± 0.002 ^a
	Unsieved powder	125.67 ± 2.08 ^b	3.72 ± 0.09 ^d	0.312 ± 0.005 ^b	6.37 ± 0.14 ^c	19.41 ± 0.36 ^d	0.904 ± 0.001 ^b	0.819 ± 0.001 ^a

Means ± standard deviations with different superscripted letters within the same column differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

thus the latter powders had probably a higher fraction surface fat, making them stickier.

Whatever the plant type, the sieving process provided sufficient amounts of all considered granulometric classes, as the lower mass fractions retained on sieves of different meshes were still superior to 10% (w/w). Sieving efficiency decreased in the following order: *H. sabdariffa* > *D. glomerata* > *B. senegalensis*. Indeed, mass fractions of the < 180 and 180–212 μm granulometric classes of *H. sabdariffa* and *D. glomerata* were more represented than other granulometric classes, whereas it was the opposite for *B. senegalensis*. This was unexpected owing to particle size distributions of unsieved powders of *B. senegalensis*, *D. glomerata* and *H. sabdariffa*: in fact, *B. senegalensis* unsieved powder being richer in fine particles, markedly higher mass fractions were expected for its < 180 and 180–212 μm granulometric classes. However, during sieving analysis, *B. senegalensis* powder was extremely sticky and cohesive, so it agglomerated and adhered to the sieves, resulting in sieve mesh blockage. So, sieving did not allow particles powder of *B. senegalensis* to be perfectly separated in granulometric classes composed of particles well different in size. Hareland (1994) reported similar observations on soft wheat flours which did not pass freely through the sieve openings.

Water activity

Water activity (a_w) which describes the degree, to which water is bound to food components, is a crucial parameter for food quality and safety (Roos, 2002). A higher a_w value indicates more free water available for biochemical reactions or microbial growth, hence shorter shelf-life (Quek et al., 2007). For all plant powders, water activity ranged from 0.207 ± 0.023 to 0.331 ± 0.001 (Table 2), which was far below the threshold ($a_w = 0.6$) for the growth of most microorganisms (molds, yeasts and bacteria) Tapia et al., 2007). Thus, all investigated powders can be considered as biochemically and microbiologically stable. Water activity of *B. senegalensis* and *H. sabdariffa* powders increased significantly ($p < 0.05$) when particle size was decreased. This was consistent with the fact that the higher specific surface area of fine particles (due to their higher surface-to-volume ratio) offered a larger contact area with the surrounding air and increased interactions with air humidity, enhancing water absorption and thus increasing water activity (Petit et al., 2017). This observation was also confirmed by Cid-Ortega and Guerrero-Beltrán (2014) on *H. sabdariffa* powders, who showed that water activity of finer particles (500 μm) was greater than for larger particles (1000 μm). As for *D. glomerata* powders, no significant change of water activity was denoted between the different granulometric classes. Thus, this

difference between plant samples can result from structural differences of plant tissues (fat and fiber contents for instance).

Color characteristics

Table 2 presents two parameters, chromaticity and hue angle, for studied plant powders. Results indicated that powder color parameters were affected both by the plant material and mean particle size ($p < 0.05$). *B. senegalensis* powders were predominantly white owing to their low chromaticity, this latter indicating a low degree of color saturation. Hue angles of circa 90° indicated that the main color of *B. senegalensis* powders was yellow. Consequently, these powders appeared light yellow. Particle size seemed not to influence significantly color parameters of *B. senegalensis* powders. *D. glomerata* powder samples were generally dark, but large particles were a little brighter. Color saturation was rather low and it increased with particle size: color was more pronounced for large particles. Hue angle was close to 5° , which corresponds to purple-red. Thus, *D. glomerata* powders appeared grey with a pale purple-reddish hue. On other hand, *H. sabdariffa* powder samples denoted that hue angle values were close to 5° and their chromaticity varied from 13.20 to 20.74: hence, *H. sabdariffa* powders appeared dark and purple-red. An increase in the particle size of *H. sabdariffa* powder samples was associated with decreased whiteness index, hue angle and chromaticity, indicating the increase in red-purple color for small particles. This may be indicative of the higher content in colored molecules, such as anthocyanins (Moura et al., 2018), in smaller particles of *H. sabdariffa*. In this respect, Cid-Ortega and Guerrero (Cid-Ortega and Guerrero-Beltrán, 2014) were reported values of Hue* and C* of 73.99 and 23.68; 72.39 and 18.34; 74.84 and 26.57 respectively for particle sizes of 500 μm and 1000 μm of *Hibiscus* calyces from Mexico, different to that obtained in this study.

Morphological characteristics

Shape parameters (e.g. sphericity, convexity and aspect ratio) intend to describe morphology of powder particles. As indicated in Table 2, significant differences ($p < 0.05$) were found in the sphericity and convexity values of investigated powders. Whatever the plant type, sphericity was lowered when particle size was increased. This indicated that smaller particles were more spherical and more compact (less elongated). For *B. senegalensis* powders, convexity slightly decreased with particle size, whereas the opposite was true for *D. glomerata* and *H. sabdariffa* powders. More convex particles either have an irregular shape or higher surface roughness. This could enhance

interparticular interactions by Van der Waals forces and mechanical linkage (Fatah, 2009) and thus impair powder flowability.

All in all, whatever the plant type, large particles had a more irregular shape and this may reflect the difficulty to grind some plant parts: indeed, plant organs that are hard to grind (such as those rich in fibers) are expected to result in large particles conserving an anisotropic shape (Becker et al., 2016).

Flow properties of plant powders

Basic flowability energy, density and compressibility

Flow properties of powders are listed in Table 3. Basic flowability energy (BFE) increased with particle size increase for *D. glomerata* and *H. sabdariffa* powders, and the opposite was observed for *B. senegalensis* powders. As interparticular interactions are enhanced for fine particles, owing to their higher number of contact points, more energy should be required to overcome cohesive interactions and make powder flow. This is in agreement with results obtained for *B. senegalensis* powders, but not for powders obtained from the other plant types. However, Bharadwaj et al. (2010) simulated powder resistance to flow in FT4 and showed that the flow energy was very sensitive to particle shape: irregular or rod-like particles require more flow energy than spherical particles, due to the influence of particle orientation (Nan et al., 2017).

Particle size has a considerable impact on compressibility (Table 3). Obtained compressibility values were lowest at the smaller particle size of studied plant powders. Compressibility is a measure of packing and is considered parameter for bulk handling. Higher compressibility means more space along the particle, indicating low bulk density. Thus, upon consolidation the powder can compress more. Compressibility can be also used for predicting whether the powder is free flowing or cohesive.

Conditioned Bulk and bulk densities are used to determine powder expansion or interparticular porosity. They also indicate the volume of packaged material (Shafi et al., 2016). It is well established that food powder quality can be controlled by particle size, bulk density tapped density (Hu et al., 2012). Conditioned bulk density and density after compaction at 9 kPa of investigated powders are shown in Table 3. Conditioned bulk density was similar (around 0.4 kg/m³) for all powders, whatever the plant type and mean particle size. After compaction at 9 kPa, density increased markedly and significant differences were denoted between granulometric classes: smaller particles led to lower densities after compaction, suggesting that interparticular voids were more numerous for powder

samples composed of smaller particles, thus offering a larger surface in contact with the surroundings (Hu et al., 2012).

Singh and Prasad (2013) and Zhao et al. (2015) reported similar trends of the influence of particle size on tapped density for *Moringa oleifera* leaves and red grape pomace powders, respectively. However, Sharma et al. (2013) found that mango pulp powders had higher tapped density when particles were smaller, but this surely derived from the monodisperse character of powders studied by these authors.

Flowability in high-stress conditions

Shear cell test permits to investigate the rheological behavior of powders submitted to high levels of normal stress, like in hoppers of big bags (Table 3). Powder cohesion was rather high for *B. senegalensis* and *D. glomerata* powders and it increased with particle size. The opposite was obtained for *H. sabdariffa* powders: cohesion was rather low and seemed to decrease with particle size. The other factor for lowest cohesion values for *H. sabdariffa* powder samples was due to the difference in chemical composition. Indeed, the obtained protein and fat contents were lowest in *H. sabdariffa* powders samples, compared to those of *B. senegalensis* and *D. glomerata* powders. The presence of higher surface lipid and protein in particle powders could be another reason for the higher cohesion values. Indeed, protein and fat have a similar trend on the cohesion values due to the contribution of these components in strengthening the inter-particle interactions through chemical bonding. Protein and fat tend to form non-covalent hydrogen bonds (protein), chemicals links (protein and fat), or liquid fat bridges (fats) (Landillon et al., 2008).

Flow function values confirmed that cohesive powders had lower flowability. Indeed, *B. senegalensis* and *D. glomerata* powders were classified from easy-flowing to cohesive powders based on ff values, whereas *H. sabdariffa* powders ranged from easy-flowing to free-flowing. The deleterious influence of particle size on flowability of *B. senegalensis* and *D. glomerata* powders was also evidenced through ff results. These observations correlate well with sphericity and convexity results. Indeed, it has been evidenced by granulomorphometry that larger particles of plant powders were more irregular, thus favoring physical interlocking of particles. Thus, a high cohesion was expected for granulometric classes composed of large particles, therefore restricting their aptitude to flow (Ambrose et al., 2016; Nan et al., 2017). For *H. sabdariffa* powders, no clear influence of mean particle size could be drawn from ff values, but it appeared that flowability was maximized for granulometric classes of intermediate size

Table 3 Flowing parameters obtained from FT4 stability, compressibility and shear tests for granulometric classes and unsieved powders of *Boscia senegalensis*, *Dichrostachys glomerata* and *Hibiscus sabdariffa*

Plants	Powder samples	Basic flowability energy (mJ)	Conditioned bulk density (g/mL)	Compressibility (%)	Cohesion (kPa)	Flow factor (—)	Bulk density at 9 kPa (g/mL)	Flow classification
<i>Boscia senegalensis</i>	< 180 µm	90.15 ± 4.39 ^c	0.42 ± 0.03 ^{ab}	25.74 ± 3.42 ^a	1.63 ± 0.15 ^a	2.73 ± 0.17 ^b	0.58 ± 0.04 ^a	Cohesive
	180–212 µm	87.01 ± 3.35 ^{bc}	0.42 ± 0.03 ^{ab}	46.29 ± 3.17 ^b	1.80 ± 0.08 ^{ab}	2.51 ± 0.08 ^{ab}	0.70 ± 0.01 ^b	Cohesive
	212–315 µm	83.53 ± 1.46 ^{ab}	0.42 ± 0.01 ^{ab}	44.57 ± 3.32 ^b	1.87 ± 0.03 ^b	2.44 ± 0.05 ^a	0.75 ± 0.05 ^b	Cohesive
	> 315 µm	79.68 ± 0.95 ^a	0.44 ± 0.01 ^b	43.44 ± 1.63 ^b	1.93 ± 0.16 ^b	2.39 ± 0.16 ^a	0.79 ± 0.01 ^b	Cohesive
	Unsieved powder	86.29 ± 2.55 ^{bc}	0.39 ± 0.01 ^a	29.91 ± 1.62 ^a	1.77 ± 0.10 ^{ab}	2.56 ± 0.11 ^{ab}	0.53 ± 0.03 ^a	Cohesive
<i>Dichrostachys glomerata</i>	< 180 µm	134.60 ± 1.33 ^a	0.42 ± 0.02 ^a	35.50 ± 1.69 ^a	0.66 ± 0.08 ^a	7.01 ± 0.70 ^c	0.62 ± 0.03 ^a	Easy flow
	180–212 µm	147.57 ± 5.73 ^b	0.42 ± 0.03 ^a	50.24 ± 4.33 ^{bc}	1.80 ± 0.02 ^b	2.30 ± 0.03 ^a	0.84 ± 0.01 ^c	Cohesive
	212–315 µm	134.60 ± 1.33 ^a	0.42 ± 0.02 ^a	54.08 ± 3.68 ^c	1.71 ± 0.37 ^b	2.52 ± 0.39 ^a	0.78 ± 0.08 ^{bc}	Cohesive
	> 315 µm	186.35 ± 3.89 ^c	0.41 ± 0.01 ^a	45.08 ± 2.66 ^b	1.73 ± 0.18 ^b	2.49 ± 0.20 ^a	0.83 ± 0.07 ^{bc}	Cohesive
	Unsieved powder	147.23 ± 5.01 ^b	0.39 ± 0.02 ^a	31.30 ± 3.65 ^a	1.00 ± 0.11 ^a	5.00 ± 0.43 ^b	0.67 ± 0.05 ^{ab}	Easy flow
<i>Hibiscus sabdariffa</i>	< 180 µm	113.70 ± 4.41 ^a	0.41 ± 0.05 ^b	32.21 ± 2.29 ^b	0.70 ± 0.07 ^c	7.25 ± 0.18 ^b	0.64 ± 0.01 ^a	Easy flow
	180–212 µm	205.72 ± 3.37 ^c	0.36 ± 0.01 ^a	47.06 ± 0.35 ^d	0.40 ± 0.03 ^b	11.39 ± 0.17 ^c	0.66 ± 0.02 ^a	Free flow
	212–315 µm	211.01 ± 1.49 ^c	0.43 ± 0.02 ^{bc}	35.01 ± 3.26 ^b	0.36 ± 0.05 ^a	14.44 ± 0.46 ^c	0.66 ± 0.01 ^a	Free flow
	> 315 µm	212.88 ± 7.76 ^c	0.48 ± 0.05 ^c	26.33 ± 1.94 ^a	0.42 ± 0.01 ^a	12.09 ± 0.45 ^d	0.65 ± 0.05 ^a	Free flow
	Unsieved powder	150.45 ± 1.11 ^b	0.41 ± 0.01 ^b	43.30 ± 1.23 ^c	0.94 ± 0.01 ^d	5.11 ± 0.01 ^a	0.72 ± 0.01 ^b	Easy flow

Means ± standard deviations with different superscripted letters within the same column differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

(212–315 μm). This may arise from the combination of the deleterious influence of shape irregularity of large particles and the higher cohesion of small particles (due to the higher number of contact points between small particles (Nan et al., 2017; Szulc and Lenart, 2016). The latter phenomenon has been evidenced by Fitzpatrick et al. (2005) for corn starch powder, cocoa powder, wheat flour and soy flour, who showed that powders with smaller particle size tend to have a smaller flow index.

The flowability was significantly affected by compressibility. The less compressible the powder, the better it flows. It was consistent with literature, where powders with high compressibility are deemed to have low flowability (Fayed and Skocir, 1997).

Hydration properties of plant powders

The modification of particle size and shape is also expected to influence hydration properties, such as water absorption capacity (WAC), water solubility index (WSI) and dispersibility. Indeed, particles dispersibility in water is an index used to estimate aptitude for powder rehydration. Hydration characteristics of *B. senegalensis*, *D. glomerata* and *H. sabdariffa* powders are gathered in Table 4. All in all, when particle size was increased, water absorption

capacity, water solubility index and dispersibility significantly decreased ($p < 0.05$), indicating that interaction with water was improved for smaller particles. This surely came from the larger specific surface area of smaller particles (owing to their greater surface-to-volume ratio). When, thus increasing the surface area available for solvation by water (Ye et al., 2016). Moreover, size reduction of plant material can create new surface hydrophilic groups from cellulose and hemicellulose, which enhance interactions with water (Ting et al., 2014). The results of the current study meet the work of Singh and Prasad (2013), who also reported a decrease in WAC of *Moringa oleifera* leaf powders for larger particles.

Correlations between physicochemical and flow properties

Principal components analysis (PCA) was performed to evidence correlations between physicochemical characteristics and flow properties of powders issued from *B. senegalensis*, *D. glomerata* and *H. sabdariffa* (Fig. 1). The principal components PC1 and PC2 represented a total of 71.94% variation of powder properties. The distribution of powder samples on the PC1 $\times$ PC2 plot revealed a separation of powder samples according to plant type. *D.*

Table 4 Hydration properties of granulometric classes and unsieved powders of *Boscia senegalensis*, *Dichrostachys glomerata* and *Hibiscus sabdariffa*

Plants	Powder samples	Water absorption capacity (g/g dry matter)	Water solubility index (g/100 g dry matter)	Dispersibility (%)
<i>Boscia senegalensis</i>	< 180 μm	3.69 ± 0.01^c	32.03 ± 0.27^{ab}	37.92 ± 0.97^{bc}
	180–212 μm	3.63 ± 0.01^{bc}	31.71 ± 0.05^a	36.06 ± 0.74^b
	212–315 μm	3.54 ± 0.11^{ab}	32.17 ± 0.15^{ab}	38.15 ± 1.37^{bc}
	> 315 μm	3.55 ± 0.09^{ab}	32.74 ± 0.78^b	39.41 ± 0.34^c
	Unsieved powder	3.51 ± 0.03^a	32.17 ± 0.74^{ab}	32.65 ± 2.49^a
<i>Dichrostachys glomerata</i>	< 180 μm	4.93 ± 0.04^c	37.81 ± 0.52^c	36.33 ± 0.75^c
	180–212 μm	4.74 ± 0.07^b	26.04 ± 0.38^b	42.57 ± 2.07^d
	212–315 μm	4.42 ± 0.17^a	25.69 ± 0.89^b	31.57 ± 1.47^b
	> 315 μm	4.46 ± 0.04^a	22.58 ± 0.84^a	26.64 ± 0.70^a
	Unsieved powder	4.68 ± 0.05^b	23.60 ± 0.30^a	37.48 ± 1.36^c
<i>Hibiscus sabdariffa</i>	< 180 μm	5.71 ± 0.17^{bc}	42.47 ± 0.37^b	67.43 ± 2.29^e
	180–212 μm	5.52 ± 0.28^{ab}	51.41 ± 1.26^d	47.86 ± 2.44^c
	212–315 μm	5.53 ± 0.12^{ab}	45.04 ± 0.29^c	33.39 ± 0.70^b
	> 315 μm	5.28 ± 0.10^a	40.64 ± 0.19^a	25.70 ± 0.84^a
	Unsieved powder	6.04 ± 0.29^c	41.48 ± 0.62^{ab}	56.36 ± 2.42^d

Means $\pm$ standard deviations with different superscripted letters within the same column differed significantly ($p < 0.05$) according to Duncan's multiple range test ($n = 3$)

Fig. 1 Principal Components Analysis of physicochemical and functional properties of investigated plant powders (unsieved powders and granulometric classes). BS: *Boscia senegalensis*, DG: *Dichrostachys glomerata*, HS: *Hibiscus sabdariffa*

glomerata powder samples were associated with high fiber content, particle size (D_{50}), conditioned bulk density and compressibility, low water activity, dispersibility, carbohydrates content, WSI and dispersibility, and in a lesser extent high convexity, flow energy and cohesion. All in all, *D. glomerata* had high fiber content and resulted in the formation of large irregular particles by grinding, leading to powders having low flowability and hydration properties. *H. sabdariffa* powders were characterized by high flow factor, ash content, WAC and WSI, low cohesion and in a lesser extent high carbohydrates content, dispersibility, water activity and moisture content along with low compressibility. This denoted that these powders had the better flowability and hydration properties within all investigated powders. The good rehydration properties may be related to the relatively high contents in water and carbohydrates (hydrophilic compounds). Last, *B. senegalensis* powders were correlated to high protein and fat contents, span, elongation, low convexity, basic flowability energy and moisture content and in a lesser extent high sphericity and

cohesion and low WAC and fiber content. Thus, these powders exhibited intermediate flow and hydration properties, which can be related to their high fat content (impairing flow and rehydration) and regular particle shape (improving functional properties). Meanwhile, particle size (D_{50}) is expected to influence powder cohesion or caking ability, as large particles and/or non-spherical have more contact points and thus are able to form more bridges (electrostatic, mechanical) between them. Thus, the large particle size exhibited higher powder cohesion, conditioned bulk density and compressibility. However, the large particle size is in discredit of powder rehydration (the lowest were the values of WAC, WSI and dispersibility), this explain the lowest specific surface of the large particle powders.

This study permitted to investigate the effects of size reduction technology on the physicochemical characteristics, flow behavior and hydration properties of *Boscia senegalensis*, *Dichrostachys glomerata* and *Hibiscus sabdariffa* powders. A significant impact of particle size was

evidenced on physicochemical and hydration properties of studied plant powders. Granulometric classes with smaller particle sizes contained more protein, fat and ash, but fewer carbohydrates and fibers. Furthermore, smaller particles had a more regular shape (higher sphericity and lower elongation). These physicochemical characteristics were correlated with functional properties and it was shown that water activity, water absorption capacity, water solubility index and dispersibility increased when decreasing the mean particle size of plant powders. Powders flow characteristics clearly showed that differences in particle size distribution and particularly particle shape significantly affected all flow properties.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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