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Some simplified geometrical properties of elephant grass and sugarcane trash particles

Edgardo Olivares Gómez [a,*], Luís Augusto Barbosa Cortez [b], Guillermo Roca Alarcon [c], George Jackson de Moraes Rocha [a], Vinicius Fernandes Nunes da Silva [a], Eduardo de Almeida [d]

[a] *Laboratório Nacional de Ciência e Tecnologia do Bioetanol — CTBE, Campinas, São Paulo, Brazil*
[b] *Faculdade de Engenharia Agrícola — FEAGRI, Universidade Estadual de Campinas, São Paulo, Brazil*
[c] *Facultad de Ingenieria Mecánica — FIM, Universidad de Oriente, Santiago de Cuba, Cuba*
[d] *Faculdade de Engenharia Química — FEQ, Universidade Estadual de Campinas, São Paulo, Brazil*

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ABSTRACT

Two types of biomass solid particles, elephant grass ("*Pennisetum purpureum Schum.*" variety) and sugarcane trash have been studied in laboratory in order to obtain information about several geometrical properties. In both cases, the length, width, and thickness of fifty randomly selected particles from the fractions of each size class or group of particles, obtained by mechanical fractioning through sieves, were measured manually given their sizes. A geometric model of rectangular base prism type was adopted based on observations. It was demonstrated that most of the measured particles exhibited lengths significantly greater than width ($l \gg a$). From those measurements, average values for other geometrical properties were estimated; for example, shape factor, sphericity, particle specific surface areas, equivalent diameter, etc. A statistical analysis was done, and empirical and semi-empirical mathematical correlation models were proposed. These correlation models were obtained by non-linear regression analysis to describe the characteristic dimension of particle dependence on geometrical properties, which proved to be a good fit for the reported experimental data.

1. Introduction

A proper knowledge of the physical and chemical properties of the fuels is essential in order to design biochemical and thermochemical conversion processes and equipments. The lack of standards for characterizing solid biomass fuels makes it difficult to achieve an adequate understanding and meaningful comparison of the experimentally determined properties.

Most recently, some investigators have focused on elephant grass (a family of grasses) and sugarcane trash, which are lignocellulosic materials with potential value to biofuels and bioenergy production [1]. The energetic potential of these sources of lignocellulosic materials is comparable to that of wood, but with significantly lower moisture content in the initial condition of use. Also, early investigations of ethanol recovery from enzymatic hydrolysis by the National Renewable Energy Laboratory (NREL) in Colorado, United States, and Laboratório Nacional de Ciência e Tecnologia do Bioetanol (CTBE) in Campinas, São Paulo, Brazil indicate that switchgrass and sugarcane bagasse respectively are a very suitable substrate and produce high ethanol yields from current simultaneous saccharification and fermentation technology (SSFT). The materials above appointed may be considered as an agrofiber source for pulping and it appears to be a promising substitute for some woods in the production of paper. They have a relatively high cellulose content, relatively low ash content, and good fiber length to width ratios [2].

Research work involving fluid–particle interactions or both separated phases require knowledge of physical and geometrical properties. Solid phase is characterized by the knowledge of its density, particle size distribution and particle shape. These properties have a significant influence on some mechanical handling and processing operations, as well as developing technologies. Particularly, the sugarcane bagasse is a fibrous residue resultant from the sugarcane milling, composed basically by two types of particles; the fiber and the pitch [3,4]. The fiber is composed of fibrovascular bunches that give it hardness and are transport elements. The pitch is formed by spongy parenchyma cells where it accumulates the juice containing the sugars (sucrose). The sugarcane trash is a fibrous material constituted basically by green leaves, dry leaves and foliage of the plant. Bagasse and trash represent 2/3 of the sugarcane energy and 52% of the plant total mass.

Ponce et al. [3] have studied the particles apparent density as well as the geometrical properties of different sugarcane bagasse fractions. That study was based on the direct measurement of the three particle dimensions: length, width and thickness, having chosen a rectangular base prism as the geometrical model in order to characterize the particles.

* Corresponding author. Tel.: +55 19 3518 3123; fax: +55 19 3518 3164.
E-mail address: edgardo.olivares@bioetanol.org.br (E.O. Gómez).

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Geldart [5] compared several methods during the evaluation of physical and geometrical properties such as sphericity and apparent density of porous particles like those of glass, sand and calcareous. Bernhardt [4] and Ramirez and Lagunas [6] published their experimental results on the determination of volume and surface shape factors for each fraction of classifying sugarcane bagasse, and also of the total specific surface area of the sugarcane bagasse particles (m^2/g or mm^2/g) according to the following relation:

$$s_e = \frac{a_s}{a_v \rho_a} \int_0^\infty \frac{1}{X_i} \frac{dM_i}{dX_i} dX_i \tag{1}$$

Where:

- s_e Total specific surface area of the particles (m^2/g or mm^2/g);
- a_s and a_v Shape factors for area and volume in the respective size class of the particles of material, dimensionless;
- ρ_a Particle apparent density, kg/m^3;
- X_i Characteristic dimension in the respective size class of the particles of material, m;
- M_i Mass fraction in the respective size class of the particles of material, dimensionless.

And the specific volumetric surface area of the material particles (or samples) in m^2/m^3 (or mm^2/mm^3), according to following relation:

$$s_v = s_e \rho_a (1 - \varepsilon) \tag{2}$$

Where:

- s_v Specific volumetric surface area of the material particles (m^2/m^3 or mm^2/mm^3);
- ε mean conglomerate porosity, dimensionless.

The literature does not provide any information about physical and geometrical properties for elephant grass and sugarcane trash materials, that allows to evaluate its use as lignocellulosic feedstock on the fast pyrolysis and gasification processes, commonly conducted in packed and fluidized bed reactors to produce charcoal, liquid biofuels, biosyngas and ethanol by hydrolysis process, also on the pneumatic and hydraulic conveying systems, drying systems, pneumatic and mechanical classifying systems, and others.

Thus, the objective of this study was to develop a new and simplified methodology for approximately determining the shape factor, surface shape factor, volume shape factor, sphericity, specific surface area and other geometrical properties, totalizing eighteen geometrical properties determined for seven size fractions of elephant grass and sugarcane trash particles. For this purpose, a protocol for the experimental and theoretical determination of geometrical properties of biomass solid particles was developed. As a first approach this methodology can be applied to any biomass particle with several moisture contents.

Empirical mathematical models were proposed for ten properties of those determined and obtained through non-linear regression analysis. The determination coefficient for each empirical or semi-empirical model to verify a good fit for the reported experimental data was used.

Quantitative data values of these properties studied here are the basic data for designing different systems, such as, pneumatic classification systems, conveyor belts, storage silos and several biochemical and thermochemical reactors.

2. Theoretical approach

Usually, standard methods for physical and chemical analyses applied to coal and coke as well as those for wood have been adapted and utilized for characterization of polidisperse biomass fuels. However, the characterization results for such materials as sugarcane bagasse and trash, elephant grass, rice husk, coffee straw, and other biomass, are, most of the time, inconsistent and the yield results are difficult to interpret. In fact, ASTM (American Society for Testing and Materials) methods are applied to quite dense materials whose physical distribution characteristics are very different from those of renewable nature. On the other hand, polidisperse biomass fuels, such as sugarcane bagasse and trash, and those above cited, have low density and complex size and shape distributions of particles. For these types of biomass, the normalized techniques used for physical and geometrical analyses of biomass fuel particles are not usually mentioned.

It is necessary to understand the particle size distribution analysis (PSDA) for those materials, which constitute also a field of numerous and different reported results due to the complex nature of these solid materials and the lack of detailed description of the adapted methodology. It's said that there is not a unique opinion about the size and shape of the particles which can be represented using an exact probability density function to describe the distribution of particles of these materials according to their sizes.

The biomass particulate system models studied consist of porous particles having a wide size distribution and non-spherical shapes. Other characteristics of these particulate models of representative samples are often difficult to be obtained as well as the particle size distribution (PSD) experiments have commonly lower reproducibility and reliability because of the difficulty in handling biomass samples.

After obtaining each mass fraction, the material was replaced to direct handling in order to verify visually the particle morphological structure (shape and dimensions of particles). This observation process allows associating the shape of the particles to some simple geometrical model (Fig. 1), and by this way there is a space representation for the particle dimensions.

The literature presents the usage of the two applicable geometric models, in most cases, to sugarcane bagasse. These models are for the fiber particles, a model of elliptic/cylindrical base prism, and for the pitch particles a spherical model.

In this case, the geometrical and morphological behavior of particles on each examined size classes were obtained analyzing particles having high length/width ratios, which were approximated to a rectangular base prism with parallel flat faces (parallelepiped). Particles of regular shape type (cubic space model), commonly represented with length/width ratio near unity, and spherical particles were not noticed. So, linear measures for length, width and thickness were taken for each particle.

The relationships used and their preliminary definitions for the estimation of all physical and geometrical properties were the following:

- Characteristic dimension, X_i, mm [4]: The parameter used for identifying the characteristic dimension of the i-th mass fraction of the polidispersed particles.

$$X_i = \bar{X}_{i-th} = \left[\frac{\left(X_2^2 + X_1^2\right)(X_2 + X_1)}{4}\right]^{1/3} \tag{3}$$

- Projected area of the particle (rectangular base prism model), A_{proj}, mm^2 [3,4]:

$$A_{proj} = q.a.l \tag{4}$$

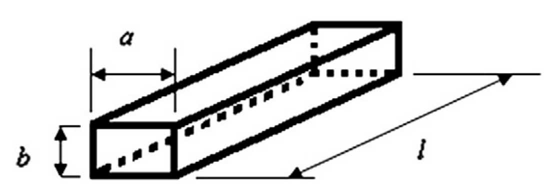

Fig. 1. Assumed geometrical model (rectangular base prism or parallelepiped).

- Area of the transversal section of the particle (rectangular base prism model), A_{stpris}, mm^2 [3,4]:

$$A_{stpris} = a.b \tag{5}$$

- Volume of the particle (rectangular base prism model), V_p, mm^3 [3,4]:

$$V_p = r.q.a.b.l \tag{6}$$

Where:

a, b and l are the width, thickness and length of particle respectively.
q and r are the correction factors of the deviation produced in the association of the particle's shapes with the most similar geometric shape. According to our geometric model, the given values for q and $r$are both assumed to be 0.75 [4].

- Particles apparent density of each size class, ρ_a, kg/m^3:

$$\rho_a = {}^{\sum m_i}\Big/_{\sum V_{p_i}} \tag{7}$$

When Eq. (7) is utilized it must be made a random selection of the particles for each size class. Each selected particle of the conglomerate must be weighed and their three basic dimensions must be measured. Then, an average mass value must be calculated and divided by the average volume value calculated from the average dimensions data, as follows:

$$\bar{\rho}_a = \left[\left({}^{\bar{m}_p}\Big/_{\bar{V}_p}\right)\right]_{clase} \tag{8}$$

So that (by Eq. (6)):

$$\bar{V}_p = r.q.\bar{a}.\bar{b}.\bar{l} \tag{9}$$

Where:

$\bar{a}$, $\bar{b}$ and $\bar{l}$ are the average width, thickness and length of particle

And considering that $r = q = 0.75$, we finally would have:

$$\bar{V}_p = 0.5625\bar{a}.\bar{b}.\bar{l} \tag{10}$$

In this work the particle's apparent and real density of the elephant grass and sugarcane trash were obtained using a mercury intrusion porosimetry technique (ASTM Norm D 4404-84 (1998) — Test method for determination of pore volume and pore volume distribution of soil and rock by mercury intrusion porosimetry).
The density of a material is defined as the mass of a quantity of it divided by the volume of that same quantity (kg/m3). Three kinds of densities are determined:

1) The absolute density of the material is also called the real or skeletal density. It is obtained when the volume measured excludes the pores within the material sample. Water for its determination or any other liquid which is expected to fill pores can be used, removing their volume from the measurement. In this case mercury was used which was forced into pores giving absolute density values. The technique used is named mercury intrusion porosimetry and the equipment was the Porosimeter Autoscan 60, Quantachrome and Autoscan Filling Aparatus Quantachrome at the Grupo de Combustíveis Alternativos, Departamento de Física Aplicada, Universidade Estadual de Campinas — UNICAMP, Campinas, São Paulo, Brazil. The ASTM D 4404-84 (1998 Norm) was used. Gas pycnometers can also be used to determine the material absolute density. In this case the helium gas pycnometers are much more used; the apparent density or envelope density of the particles is determined for porous material when pore spaces within the material are included in the volume measurement.
2) Envelope density values are necessarily less than absolute densities when the material is porous. Also this physical property is determined by mercury porosimetry or gas pycnometry. In this case the envelope density was determined using Quantachrome Autoscan Mercury Porosimetry technique. The ASTM D 4404-84 (1998 Norm) was used.
One of the most used techniques for determining the real density as well as the apparent density of the particle is the porosimetry technique through mercury intrusion. Intrusion pressure — mercury does not wet most substances and will not penetrate pores by capillary actions. It has to be forced to do so. Entry into pore spaces requires applying pressure in inverse proportion to opening size. This pressure is named intrusion pressure and is applied to the mercury column on the essential part of porosimeter called penetrometer.
3) Bulk density is obtained from filling a container with the sample material and vibrating it to obtain near optimum packing, depending on the vigor and number of taps (on mechanical devices); bulk density is not only an inherent property of the material, but is also dependent on the particle size distribution and shape. Bulk density is always a smaller value than envelope or apparent density.

- Shape factor, ψ, dimensionless [4]: The relation between the surface area of the spherical equivalent and the actual surface area of the particle both with the same volume:

$$\psi = \left[\left({}^{A_{s_{sphere}}}\Big/_{A_s}\right)\right]_v \tag{11}$$

In this case,

$$\psi = \left[\left({}^{\pi D_{eq}^2}\Big/_{2(al+bl+ab)}\right)\right]_v \tag{12}$$

- Area shape factor, ψ_s, dimensionless [4]:

$$\psi_s = \left({}^{A_{s_i}}\Big/_{X_i^2}\right) \tag{13}$$

- Volume shape factor, ψ_v, dimensionless [4]:

$$\psi_v = \left({}^{V_{p_i}}\Big/_{X_i^3}\right) \tag{14}$$

- Factor Ratio, relation between area shape factor and volume shape factor, dimensionless [4]:

$${}^{\psi_s}\Big/_{\psi_v} \tag{15}$$

- Relation between mass fraction and characteristic dimension of the amount of particles, 1/mm:

$${}^{m_i}\Big/_{X_i} \tag{16}$$

- Surface area of the particle, A_s, mm^2:

$$A_s = 2(a.l + b.l + a.b) \tag{17}$$

- Equivalent diameter, D_{eq}, mm: is the diameter of the sphere that has the same volume of the particle. Considering the geometrical

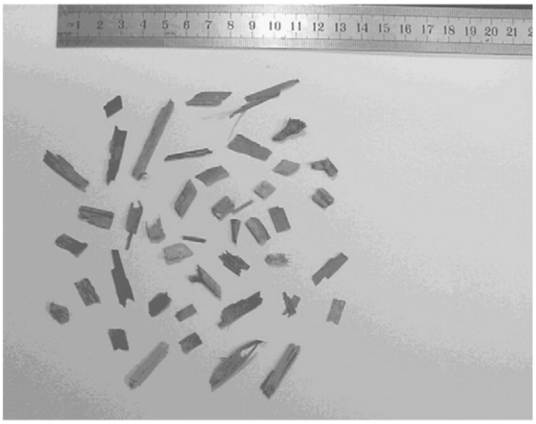

Fig. 2. Photo of elephant grass particles (−11.2 + 6.35 mm of size class).

model assumed in this case for the study of the physical and geometrical characteristics of the biomass particles:

$$D_{eq} = \sqrt[3]{(3.375a.b.l)/\pi} \quad (18)$$

- Sphericity (or Sphericity shape factor),φ, dimensionless [7]: The relation between the projection area of the sphere and the projection area of the particle, both with the same volume:

$$\varphi = \left[\left(A_{p_e} / A_p\right)\right]_v \quad (19)$$

For the equal volume condition the equivalent diameter of the particle D_{eq} was used, for which:

$$A_{p_e} = \pi D_{eq}^2 / 4 \quad (20)$$

Considering the geometrical model assumed (rectangular base prism), it will be:

$$A_p = q.a.l \quad (21)$$

and finally,

$$\varphi = \left[\left(\pi D_{eq}^2 / 4.q.a.l\right)\right]_v \quad (22)$$

-Total specific surface area of the particles,s, mm^2/g [4,8]: This parameter is conceptually defined through the following equation:

$$s_e = \int_0^\infty \psi_s.X^2 \frac{dN}{dX} dX/M \quad (23)$$

Where:

N is the number of particles that has X as its diameter;
M is the mass of those amounts of particles;
ψ_s is the surface shape factor. The relation $(\psi_s.X^2) = A_s$ is the surface area of the particles;
X is the characteristic dimension of those amounts of particles.

Considering that:

$$\frac{dN}{dX} = \left(M / \rho_a(\psi_v.X^3)\right) \frac{dM_i}{dX} \quad (24)$$

Where:

M_i is the mass fraction parameter of the material, and integrating the equation from s it is obtained a simple expression for the calculation of the specific surface area in mm^2/g as following:

$$s_e = \left(\psi_s / \rho_a.\psi_v\right) \sum \left(M_i / X_i\right). \quad (25)$$

Eq. (25) assumes that the shape factors ψ_s and ψ_v are constant over the entire range of particle sizes particularly examined.

3. Experimental

Samples of elephant grass were preprocessed physically by milling and donated for this study by "Instituto de Zootecnia" in Nova Odessa, São Paulo, Brazil. The samples of sugarcane trash were also preprocessed physically by milling and donated by "Laboratório Nacional de Ciência e Tecnologia do Bioetanol — CTBE" in Campinas, Sao Paulo, Brazil. The sample moisture content was the equilibrium moisture, 10.5% ± 0.2% (wet basis) for elephant grass and 10.1% ± 0.2% (wet basis) for sugarcane trash. In this work, the elephant grass and sugarcane trash preprocessed samples were stored inside plastic bags, being kept in controlled environment of temperature and relative humidity.

The size distribution analysis for two samples of these materials was done by "Laboratório de Termodinâmica e Energia", FEAGRI, UNICAMP in Campinas, São Paulo, Brazil, using standardized sieve series in a vibratory machine for 20 min of residence time [9–11]. The utilized sieve series for elephant grass and sugarcane trash on the first and second line respectively, are shown in Table 1 (mesh aperture size of each sieve in millimeter):

These series of sieves consider sieves of principal, normal and complemented series [10,11]. Statistically we can consider that the samples, starting from the physically pre-treated material (milled) have followed the same norms and analytical procedures established for polydisperse materials, such as sugarcane bagasse. The defined samples were previously homogenized and successively divided in similar parts, being chosen and rejected some of these parts until we came to a sample of 1000 g for each studied biomass. Starting from this sample the sieving procedure was accomplished. This procedure guaranteed the representativity of each of the 50 collected particles according to each defined size class. So, each particle dimension measurement was conducted with magnifying glass, industrial rules, electronic digital caliper (resolution of 0.01 mm) and electronic digital thickness gage (resolution of 0.01 mm) depending on the dimensions of the particles. Measurements were replicated three times and average values obtained were analyzed and reported.

Figs. 2 and 3 show the actual particle model of preprocessed elephant grass and sugarcane trash used on this study, corresponding to −11.2 + 6.35 mm (particle average diameter of 8.77 mm) and −11.2 + 9.52 mm (particle average diameter of 10.36 mm) of size class respectively.

Table 1
Series of sieves for elephant grass and sugarcane trash respectively (aperture size of sieve in mm).

Elephant grass	12.7	11.2	6.35	4.76	4.00	3.36	2.38	2.00	1.68	1.19	1.00	0.84	0.59	0.42	0.297	–
Sugarcane trash	12.7	11.2	9.52	6.35	4.76	4.00	3.36	2.38	2.00	1.68	1.19	1.00	0.84	0.59	0.42	0.297

Fig. 3. Photo of sugarcane trash particles (−11.2+9.52 mm of size class).

Fig. 3 shows pieces of sugarcane trash (leaves). These pieces are the collected particles from sugarcane leaves before milling. These leaves are generated during the mechanical harvest of sugarcane and they are available in the field for agronomic use. Its usage by the industry would basically be for energy generation ends through its combustion in boilers for steam generation.

Tables 2 and 3 show the data of the particle size analysis or Particle-Size-Distribution (PSD) of two samples of elephant grass and sugarcane trash respectively.

4. Results and discussion

Figs. 4 and 5 show the mass distribution functions (accumulative distribution function and distribution density function) of a sample of elephant grass and sugarcane trash respectively. A two-modal behavior in the mass distribution density function on both samples can be observed. However, the most important information about the characteristic dimension of the particles is to be given by the second modal that corresponds to the second inflexion point (around 2 mm for elephant grass and 3 mm for sugarcane trash).

Particles belonging to each fraction were characterized geometrically according to selected model independently of its size or shape. There were no large differences regarding the particle's shape.

For each property and using the mean values calculated in each size class, the mean deviation, the mean standard deviation (considered with uncertainty parameter) and the confidence interval at 95%

Table 2
Particle-Size-Distribution (PSD) for two samples of preprocessed elephant grass.

ABNT[a] norm	Aperture size of sieve, mm	ASTM[b] norm	Aperture size of sieve, mm	Range of class size (ABNT norm)	Mean screen diameter, mm	Characteristic dimension X_i, mm	Mean retention (sample 1), %	Mean retention (sample 2), %
$^1/_2$ pol	12.7	$^1/_2$ pol	12.5	+12.7	–	11.96	4.50	4.42
$^7/_{16}$ pol	11.2	$^7/_{16}$ pol	11.2	−12.7+11.2	11.95	8.99	0.00	0.25
$^1/_4$ pol	6.35	$^1/_4$ pol	6.3	−11.2+6.35	8.77	5.59	5.75	6.88
4	4.76	4	4.75	−6.35+4.76	5.55	4.39	8.75	9.34
5	4.00	5	4.00	−4.76+4.00	4.38	3.69	3.75	3.19
6	3.36	6	3.35	−4.00+3.36	3.68	2.89	15.25	15.97
8	2.38	8	2.36	−3.36+2.38	2.87	2.19	20.25	18.43
10	2.00	10	2.00	−2.38+2.00	2.19	1.84	9.00	10.07
12	1.68	12	1.70	−2.00+1.68	1.84	1.45	7.00	7.13
16	1.19	16	1.18	−1.68+1.19	1.43	1.09	8.75	8.60
18	1.00	18	1.00	−1.19+1.00	1.09	0.92	4.25	3.93
20	0.84	20	0.85	−1.00+0.84	0.92	0.72	2.75	2.70
30	0.59	30	0.60	−0.84+0.59	0.71	0.51	4.00	4.18
40	0.42	40	0.425	−0.59+0.42	0.50	0.36	3.00	2.95
50	0.297	50	0.300	−0.42+0.297	0.36	0.19	1.75	0.98
Bottom	0.000	Bottom	0.000	−0.297+0.000	0.15	0.00	1.25	0.98
Sum							100.00	100.00

[a] ABNT — Associação Brasileira de Normas Técnicas.
[b] ASTM — American Society of Testing and Materials.

Table 3
Particle-Size-Distribution (PSD) for two samples of preprocessed sugarcane trash (sugarcane leaves).

ABNT1 norm	Aperture size of sieve, mm	ASTM2 norm	Aperture size of sieve, mm	Range of class size (ABNT norm)	Mean screen diameter, mm	Characteristic dimension $X_{i,\ mm}$	Mean retention (sample 1), %	Mean retention (sample 2), %
$^1/_2$ pol	12.7	$^1/_2$ pol	12.5	+12.7	–	11.96	8.5	8.4
$^7/_{16}$ pol	11.2	$^7/_{16}$ pol	11.2	−12.7+11.2	11.95	8.99	0.5	0.3
$^3/_8$ pol	9.52	$^3/_8$ pol	9.5	−11.2+9.52	8.77	8.04	0.3	1.0
$^1/_4$ pol	6.35	$^1/_4$ pol	6.3	−9.52+6.35	7.94	5.59	11.1	10.2
4	4.76	4	4.75	−6.35+4.76	5.55	4.39	17.4	17.5
5	4.00	5	4.00	−4.76+4.00	4.38	3.69	9.6	8.9
6	3.36	6	3.35	−4.00+3.36	3.68	2.89	11.7	12.6
8	2.38	8	2.36	−3.36+2.38	2.87	2.19	17.4	17.8
10	2.00	10	2.00	−2.38+2.00	2.19	1.84	6.5	7.1
12	1.68	12	1.70	−2.00+1.68	1.84	1.45	4.4	3.7
16	1.19	16	1.18	−1.68+1.19	1.43	1.09	5.4	6.0
18	1.00	18	1.00	−1.19+1.00	1.09	0.92	2.3	1.6
20	0.84	20	0.85	−1.00+0.84	0.92	0.72	1.8	2.0
30	0.59	30	0.60	−0.84+0.59	0.71	0.51	1.3	1.0
40	0.42	40	0.425	−0.59+0.42	0.50	0.36	0.7	0.8
50	0.297	50	0.300	−0.42+0.297	0.36	0.19	0.3	0.3
Bottom	0.000	Bottom	0.000	−0.297+0.000	0.15	0.000	0.8	0.8
Sum							100.0	100.0

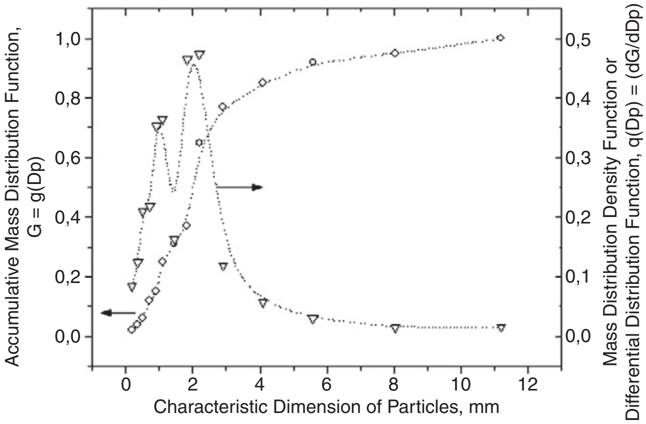

Fig. 4. Mass distribution functions of a sample of elephant grass (accumulative distribution function and mass distribution density function or differential distribution function).

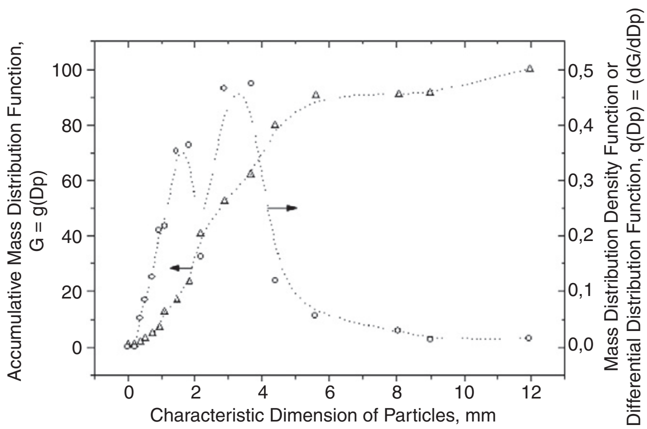

Fig. 5. Mass distribution functions of a sample of sugarcane trash (accumulative distribution function and mass distribution density function or differential distribution function).

confidence level were computed. Table 4a, 4b and 4c shows values for determined geometrical properties for elephant grass. Only 76% approximately (mass basis) of the total of particles of the sample of preprocessed elephant grass were used for the analyses and measurements, because it was in the range of particle diameter acceptable for analysis.

It must be said that the particles that went through 1.19 mm sieve were not considered in this study due to their reduced size. Particles below 1.00 mm of diameter were quantitatively not significant in the present study.

Eighteen geometrical properties for sugarcane trash are reported in Table 5a, 5b and 5c. In this case only approximately 80% (mass basis) of the total of particles of the sugarcane trash sample were used for the analysis and measurements, because it was in the range of particles diameter acceptable for analysis. In this case, the particles that went 1.68 mm sieve were not considered due to their reduced size, and particles below 1.00 mm of diameter were quantitatively not significant.

Tables 6 and 7 summarized the values of the physical properties obtained for elephant grass and sugarcane trash respectively through analytical tests. The properties are the apparent density of the particles, bulk density of material, absolute density of material, total internal surface area, total volume of pores and diameter ranges of pores. The previously mentioned properties were obtained from an initial material sample before its sieving (integral material), being the same conditioned and kept according to the norm ASTM D4404-84 [12]. The bulk density was determined, according to its definition, smoothly placing the particles, in a gauged container placed on a vibratory machine of low frequency in order to fill out a certain known volume. After this procedure the material is weighed and the density calculated using the relationship mass/volume.

R1, R2 and R3 in Tables 6 and 7 are replicates of the analytical experiments made. The values verified to apparent density of the packed material (bulk density) show coherency with the values reported in the literature for other types of particulate biomass of the similar physical characteristics [3,13–16].

Figs. 6 and 7 show, in semi-log scale, the tendencies and behavior for each studied property as functions of particles' characteristic dimension for elephant grass.

Fig. 8 shows the behavior of the approximation of the ratio ψ_s/ψ_v for elephant grass obtained over the full range of sieve sizes utilized. It is observe that the values measured and calculated were approximated by means of cubic mathematical empirical model, which was evaluated through non-linear regression for each characteristic dimension of the particle mass fractionX_i.

An empirical mathematical approximation expression for the relationship ψ_s/ψ_v versus X_i for the elephant grass has the following form:

$$\psi_s \big/ \psi_v = a_1 + b_1 X_i + b_2 X_i^2 + b_3 X_i^3 \tag{26}$$

The elephant grass parameter values examined are shown in Table 8:

The values mentioned are only applicable for a range of class sizes of the sieves smaller than 11.2 mm and greater than 1.19 mm.

Approximated empirical mathematical models of the preprocessed elephant grass relating each property as a function of particle characteristic dimension obtained by non-linear regression are shown in Table 8 with their determination coefficient R^2.

Table 4a
Geometrical properties of preprocessed elephant grass particles of each size class.

Aperture size of sieve, mm	ABNT norm	Range of class size	X_i, mm	Retention, %	Mass fraction, M_i	(M_i/X_i), 1/mm	l, mm	a, mm	b, mm
11.2	$^7/_{16}$ pol								
6.35	$^1/_4$ pol	−11.2+6.35	8.9909	6.31	0.0631	0.0072	37.15	7.03	1.12
4.76	4	−6.35+4.76	5.5917	9.04	0.0904	0.0157	32.02	5.95	1.02
3.36	6	−4.76+3.36	4.0993	15.61	0.1561	0.0359	30.76	3.45	0.68
2.38	8	−3.36+2.38	2.8973	19.34	0.1934	0.0667	15.17	3.12	0.52
2.00	10	−2.38+2.00	2.1953	9.53	0.0953	0.0459	13.67	2.36	0.48
1.68	12	−2.00+1.68	1.8445	7.06	0.0706	0.0367	12.32	1.87	0.22
1.19	14	−1.68+1.19	1.4487	8.67	0.0867	0.0616	11.22	1.50	0.14
Mean			Sum	75.56	0.7556	0.2698	21.76	3.61	0.60
MD							8.663	1.44	0.26
MSD							10.516	1.96	0.34
CI							0.233	0.043	0.007

Table 4b
Geometrical properties of preprocessed elephant grass particles of each size class.

Aperture size of sieve, mm	Aproj, cm^2	As, cm^2	Astpris, cm^2	Vp, cm^3	l/a, dimen.	l/b, dimen.	b/a, dimen.	Deq, mm
11.2								
6.35	1.9587	6.2129	0.0787	0.1645	5.2845	33.1696	0.1593	6.7973
4.76	1.4289	4.5850	0.0607	0.1093	5.3815	31.3922	0.1714	5.9312
3.36	0.7959	2.5877	0.0235	0.0406	8.9159	45.2353	0.1971	4.2633
2.38	0.3549	1.1368	0.0162	0.0138	4.8622	29.1731	0.1667	2.9788
2.00	0.2419	0.7991	0.0113	0.0087	5.7924	28.4792	0.203	2.5525
1.68	0.1728	0.5232	0.0041	0.0028	6.5882	56.0000	0.1176	1.7592
1.19	0.1262	0.3722	0.0021	0.0013	7.4800	80.1429	0.0933	1.3628
Mean	0.7256	2.3167	0.0281	0.0487	6.3292	43.3703	0.1584	3.6636
MD	0.5016	1.6089	0.0208	0.0441	0.9991	12.8168	0.0265	1.5003
MSD	0.6226	1.9855	0.0259	0.0551	2.1727	19.4160	0.0560	1.9399
CI	0.0132	0.0421	0.0005	0.0012	0.0526	0.4368	0.0013	0.0424

Table 4c
Geometrical properties of preprocessed elephant grass particles of each size class.

Aperture size of sieve, mm	Shape factor, ψ, dimen.	Sphericity, φ, dimen.	Area shape factor, ψ_s, dimen.	Volume shape factor, ψ_v, dimen.	Relation ψ_s/ψ_v, dimen.	Specific surface area, s_{e_i}, mm^2/g	Total specific surface area of particles, s_e, mm^2/g (m^2/g)
11.2							
6.35	0.2336	0.1853	7.6857	0.2264	33.9506	319.973	10,280.77
4.76	0.2410	0.1934	14.664	0.6252	23.4541	483.466	(0.01028)
3.36	0.2207	0.1794	15.399	0.5893	26.1325	1233.887	
2.38	0.2452	0.1963	13.543	0.5692	23.7915	2089.633	
2.00	0.2561	0.2115	16.581	0.8233	20.1399	1216.775	
1.68	0.1858	0.1407	15.378	0.454	33.8497	1637.154	
1.19	0.1567	0.1156	17.734	0.4359	40.6870	3299.881	
Mean	0.2199	0.1746	14.426	0.5319	28.8579	1468.681	
MD	0.0243	0.0232	1.9061	0.1198	5.47838	748.750	
MSD	0.0722	0.0584	5.0380	0.2115	10.0930	1014.562	
CI	0.0018	0.0014	0.1210	0.0049	0.2429	22.2621	

MD — mean deviation.
MSD — mean standard deviation (it's considered with uncertainty parameter).
CI — confidence interval for the mean at 5% of significance level (95% of probability).

Table 5a
Geometrical properties of sugarcane trash particles of each size class.

Aperture size of sieve, mm	ABNT norm	Range of size class	X_i, mm	Retention, %	Mass fraction, M_i	(M_i/X_i), 1/mm	l, mm	a, mm	b, mm
11.2	$^7/_{16}$ pol								
6.35	$^1/_4$ pol	−11.2 + 6.35	8.9909	10.65	0.1065	0.0120	20.05	7.71	0.68
4.76	4	−6.35 + 4.76	5.5917	17.45	0.1745	0.0343	17.84	5.95	1.02
4.00	5	−4.76 + 4.00	4.3903	9.25	0.0925	0.0187	17.31	4.27	0.31
3.36	6	−4.00 + 3.36	3.6888	12.15	0.1215	0.0359	11.13	4.02	0.42
2.38	8	−3.36 + 2.38	2.8973	17.60	0.1760	0.0612	10.55	3.10	0.29
2.00	10	−2.38 + 2.00	2.1953	6.8	0.068	0.0296	8.80	2.54	0.26
1.68	12	−2.00 + 1.68	1.8445	4.05	0.0405	0.0210	7.98	2.14	0.24
Mean			Sum	79.56	Sum	0.2127	13.38	4.25	0.46
MD							3.765	1.297	0.195
MSD							5.306	1.979	0.266
CI							0.123	0.044	0.006

Table 5b
Geometrical properties of sugarcane trash particles of each size class.

Aperture size of sieve, mm	Aproj, cm^2	As, cm^2	Astpris, cm^2	Vp, cm^3	l/a, dimen.	l/b, dimen.	b/a, dimen.	Deq, mm
11.2								
6.35	1.1594	3.4692	0.0524	0.0591	2.6005	29.4853	0.0882	4.8328
476	0.7961	2.6083	0.0607	0.0609	2.9983	17.4902	0.1714	4.8806
4	0.5543	1.6121	0.0132	0.0129	4.0538	55.8387	0.0726	2.9086
3.36	0.3356	1.0221	0.0169	0.0106	2.7686	26.5	0.1045	2.7226
2.38	0.2453	0.7333	0.0089	0.0053	3.4032	36.3793	0.0935	2.1678
2	0.1676	0.5060	0.0066	0.0033	3.4646	33.8461	0.1024	1.8412
1.68	0.1281	0.390	0.0051	0.0023	3.7290	33.25	0.1121	1.6389
Mean	0.4838	1.4773	0.0234	0.0220	3.2883	33.2557	0.1064	2.9989
MD	0.2646	0.8144	0.0166	0.0190	0.3743	6.5743	0.0177	0.9289
MSD	0.3367	1.0333	0.0201	0.0227	1.0723	13.5153	0.0402	1.3545
CI	0.0072	0.0221	0.0004	0.0005	0.0264	0.3103	0.0009	0.0304

Table 5c
Geometrical properties of sugarcane trash particles of each size class.

Aperture size of sieve, mm 11.2	Shape factor, ψ, dimen.	Sphericity, φ, dimen.	Area shape factor, ψ_s, dimen.	Volume shape factor, ψ_v, dimen.	Relation ψ_s/ψ_v, dimen.	Specific surface area, s_{e_i}, mm²/g	Total specific surface area of particles, s_e, mm²/g (m²/g)
6.35	0.2115	0.1582	4.2916	0.0813	52.7522	1075.829	13,348.93
4.76	0.2869	0.2350	8.3419	0.3483	23.9477	1396.063	(0.01335)
4.00	0.1649	0.1199	8.3636	0.1523	54.9124	1747.669	
3.36	0.2278	0.1735	7.5116	0.2106	35.6687	2171.951	
2.38	0.2013	0.1505	8.7352	0.2193	39.8221	4137.354	
2.00	0.2105	0.1588	10.499	0.3090	33.9813	1708.218	
1.68	0.2163	0.1647	11.4666	0.3674	31.2126	1111.843	
Mean	0.2170	0.1658	8.4586	0.2412	38.8996	1906.990	
MD	0.0202	0.0192	1.3314	0.0753	7.6970	623.831	
MSD	0.0729	0.0574	3.0969	0.1068	14.2822	1009.784	
CI	0.0018	0.0014	0.0733	0.0024	0.3380	23.933	

MD — mean deviation
MSD — mean standard deviation (it's considered with uncertainty parameter).
CI — confidence interval for the mean at 5% of significance level (95% of probability).

Table 6
Physical properties of elephant grass.

Physical properties	Elephant grass[a]			
	R1	R2	R3	Mean[b]
Apparent density of particle, g/cm³	0.760	0.749	0.779	0.763 ± 0.055
Absolute density of material, g/cm³[c]	1.460	1.474	1.470	1.468 ± 0.070
Bulk density of material, g/cm³ (dry basis)	0.056	0.054	0.058	0.056 ± 0.002
Diameter range of pores, °A	36–86,329	44–85,329	45–85,329	42–85,329
Intrusion pressure range, MPa	0.172–413.216	0.172–336.774	0.172–326.343	0.172–358.775
Total volume of pores, cm³/g	0.6541	0.6568	0.6557	0.6555 ± 0.0041

[a] Average moisture content of the materials of 10.5% ± 0.2% and 10.1% ± 0.2% (wet basis) respectively.
[b] Average values are reported with its confidence interval for the mean at 5% of significance level (95% of probability).
[c] Determined using the mercury pycnometry method.

Table 7
Physical properties of sugarcane trash.

Physical properties	Sugar cane trash (a)			
	R1	R2	R3	Mean (b)
Apparent density of particle, g/cm³	0.603	0.634	0.629	0.622 ± 0.050
Absolute density of material, g/cm³ c	1.414	1.411	1.361	1.395 ± 0.030
Bulk density of material, g/cm³ (dry basis)	0.050	0.045	0.049	0.048 ± 0.006
Diameter range of pores, °A	30–59,707	25–59,768	25–59,778	36–80,588
Intrusion pressure range, MPa	0.248–490.265	0.248–588.323	0.248–588.323	0.186–411.969
Total volume of pores, cm³/g	0.9507	0.9680	0.9650	0.9612 ± 0.0272

[a] Determined using the mercury pycnometry method.

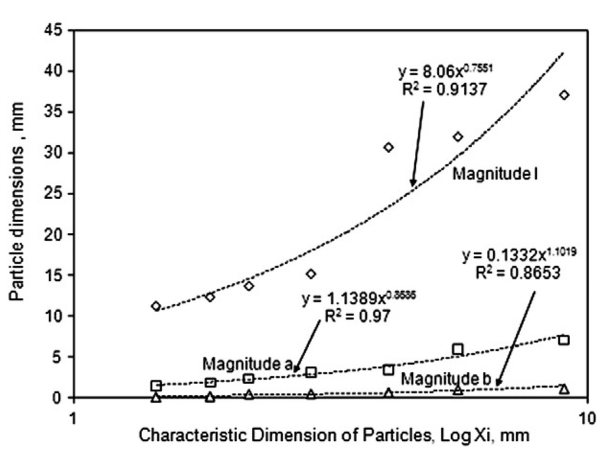

Fig. 6. Tendencies in behavior of particle dimensions in relation to their characteristic dimension — elephant grass.

Using an average particle density value of 763 kg/m³ (0.763 g/cm³) for preprocessed elephant grass, the following equation for the total specific surface area in mm²/g for this material is obtained:

$$s_e = 1/0.000763 \sum \left(\left(72.743 - 32.342X_i + 6.2351X_i^2 - 0.3471X_i^3 \right) \Big/ X_i \right) m_i \qquad (27)$$

The particle properties' relationships with a lower determination coefficient R^2 (significant scatter) are the shape factor, volume shape factor and sphericity probably due to the fact that these properties showed values that are approximately constant or with little variation in relation to the characteristic dimension of the particles over the full range of size class. For other properties, good fits of the mathematical models were assessed based on determination coefficientR^2. All properties studied show correlation models of exponential, logarithmical and polynomial type to represent the experimental data. As expected for expression $D_{eq} = 1.0951X_i^{0.9084}$ the characteristic dimension of the particles X_i has similar values to equivalent diameter of the particles.

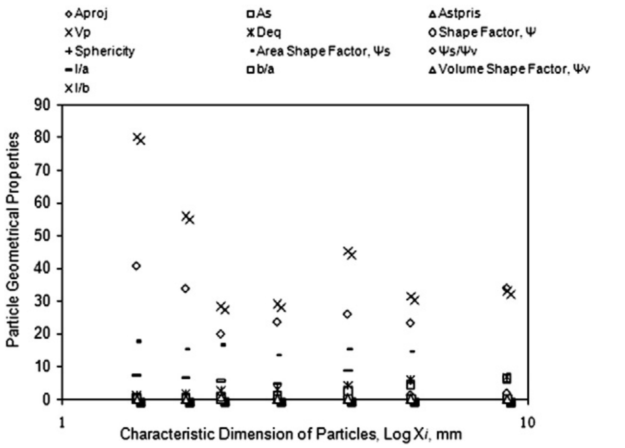

Fig. 7. Tendencies in behavior for calculated particle geometrical properties of elephant grass in relation to their characteristic dimension.

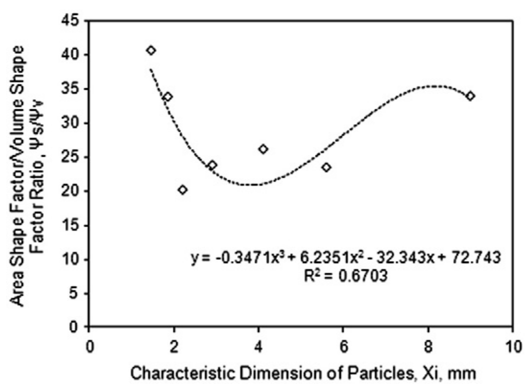

Fig. 8. Approximation of the $^{\psi_s}/_{\psi_v}$ ratio for elephant grass fractions selected by mechanical sieving.

Figs. 9 and 10 show, in semi-log scale, the tendencies and behavior for each studied particle property as functions of particles' characteristic dimension for the sugarcane trash.

Fig. 11 shows the graphical representation of the $^{\psi_s}/_{\psi_v}$ model for the sugarcane trash.

Approximated empirical mathematical models of the preprocessed sugarcane trash relating each property as a function of particle characteristic dimension obtained by non-linear regression analysis are shown in Table 9 with their determination coefficient R^2.

An empirical mathematical approximation expression for the relationship $^{\psi_s}/_{\psi_v}$ versus X_i for the sugarcane trash has the following form:

$$^{\psi_s}/_{\psi_v} = a_1 + b_1X_i + b_2X_i^2 + b_3X_i^3 \quad (28)$$

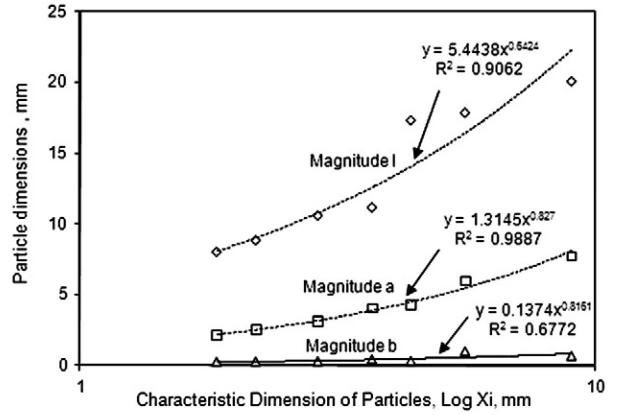

Fig. 9. Behavior of particle dimensions in respect to their characteristic dimension — sugarcane trash.

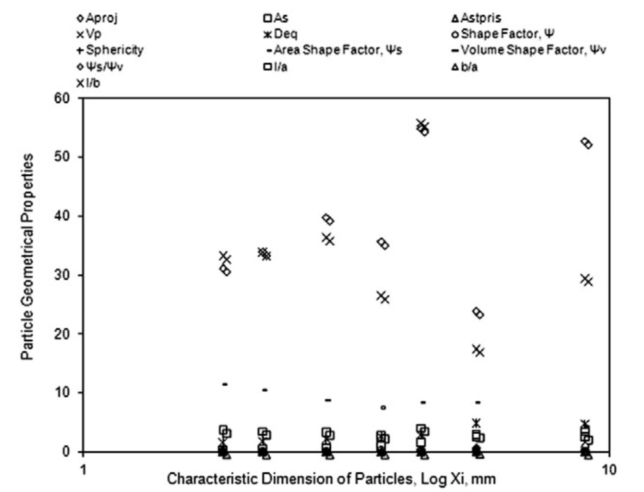

Fig. 10. Tendencies in behavior for calculated particle geometrical properties of sugarcane trash in relation to their characteristic dimension.

The values of the parameters for the sugarcane trash examined are shown in Table 9:

This approximation is only applicable for a range of class size of the sieves smaller than 11.2 mm and greater than 1.68 mm.

Using an average particle density value of 589 kg/m^3 (0.589 g/cm^3) for sugarcane trash the following equation for the total specific surface area in mm^2/g for this material is obtained:

$$s_e = 1/0.000589\sum\left(\left(-51.292+67.161X_i-14.733X_i^2+0.951X_i^3\right)\Big/_{X_i}\right)m_i \quad (29)$$

Table 8
Empirical mathematical models for the approximation of geometrical properties of elephant grass particles.

Property	Symbol	Unit	Equation	R^2
Equivalent diameter	D_{eq}	mm	$D_{eq}=1.0951X_i^{0.9084}$	0.9587
Projected area	A_{proj}	cm^2	$A_{proj}=0.0688X_i^{1.6237}$	0.9791
Transversal section area	A_{stpris}	cm^2	$A_{stpris}=0.0015X_i^{1.9705}$	0.9308
Surface area	A_s	cm^2	$A_s=0.2095X_i^{1.6554}$	0.9766
Shape factor	ψ	–	$\psi=0.1798X_i^{0.1615}$	0.3483
Area shape factor	ψ_s	–	$\psi_s=24.835-7.2507X_i+1.6213X_i^2-0.1143X_i^3$	0.9338
Volume shape factor	ψ_v	–	$\psi_v=0.7203e^{-0.0948X_i}$	0.3863
Volume	V_p	cm^3	$V_p=0.0007X_i^{2.7256}$	0.9587
Sphericity	φ	–	$\varphi=0.1368X_i^{0.1932}$	0.3366
Area shape factor to volume shape factor ratio	$^{\psi_s}/_{\psi_v}$	–	$^{\psi_s}/_{\psi_v}=72.743-32.342X_i+6.2351X_i^2-0.3471X_i^3$	0.6703

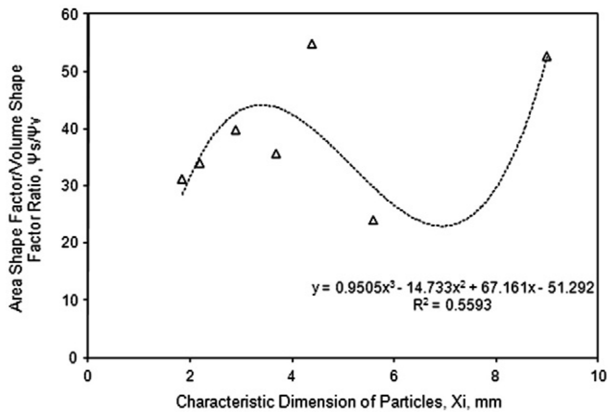

Fig. 11. Approximation of the ψ_s/ψ_v ratio for sugarcane trash fractions selected by mechanical sieving.

As may be seen for the preprocessed sugarcane trash used in this study, the particle properties' relationships with lower determination coefficient R^2 are the shape factor and sphericity. In the same way that for preprocessed elephant grass these properties showed mean values that are approximately constant or with little variation in relation to the characteristic dimension of the particles over the full range of size class. For other properties, good fits of the mathematical models were obtained, that means that its trend can be modeled although some assumptions of the model have not been verified. All properties studied show correlation models of exponential, logarithmical and polynomial type to represent the experimental data. In this case, as expected for the expression $D_{eq} = 1.0183X_i^{0.7618}$, the characteristic dimension of the particles X_i has well approximated values to equivalent diameter of the particles.

In general, little data was found in the literature which affords any comparison with the results of this study. Regarding the shape factor, mean values of 0.2199 for elephant grass and 0.2170 for sugarcane trash are lower than the one found in [3] for Cuban sugarcane bagasse of 0.55. The values of 10,280.77 (0.010) and 13,348.93 (0.013) mm^2/g (m^2/g) for the total specific surface area in relation to mass of preprocessed elephant grass and sugarcane trash respectively were 2.4 and 1.85 times lower than the one reported by [4] for sugarcane bagasse (24,700 mm^2/g). Mean specific surface in relation to volume of 111.0 cm^2/cm^3 for preprocessed elephant grass and of 112.1 for preprocessed sugarcane trash are approximately 3 times bigger respectively than the one reported by [3] for Cuban sugarcane bagasse (33.2 cm^2/cm^3).

Values of specific surface area (in units of m^2/g) for sugarcane bagasse (fiber and pitch), sugarcane trash and elephant grass (*Pennisetum purpureum Schum.* variety) were obtained in the CTBE in Brazil, being applied the analytic technique of adsorption of nitrogen, and using the model of adsorption of Brunauer, Emmett and Teller (B.E.T.) in the equipment ASAP 2020 of Micromeritics [17]. The results derived from the B.E.T. show values of 0.79 ± 0.20 m^2/g for the pitch fraction and 0.92 ± 0.10 m^2/g for the fiber fraction (250 μm of average size of particle obtained using cutting mill), both for the sugarcane bagasse, 0.7191 ± 0.1091 m^2/g for the sugarcane trash (1000 μm of average size of particle obtained using cutting mill), and of 0.6672 ± 0.1278 m^2/g for elephant grass (1000 μm of average size of particle obtained using cutting mill). Comparing these results we can verify a totally explainable agreement, every time that through the analytic technique of adsorption of N_2 it is possible to obtain much larger specific surface areas than obtained using the proposed methodology in this work. That happens because through the adsorption technique it is guaranteed that N2 penetrates in the material facing the cell wall lumen region of the biomass.

In this paper only the determination coefficient calculation for each empirical model was made. Thus, these correlations must be considered as approximated correlations.

5. Conclusions

Geometrical and physical properties from the direct measurements of particles and analytical techniques have been addressed in this study. These methods and experimental procedures can also be used for other fibrous biomass, including elephant grass or sugarcane trash. Results showed consistent average values for absolute density, apparent density, bulk density, total volume of pores and specific surface area for elephant grass and sugarcane trash in relation to other fibrous biomass, such as sugarcane bagasse. The values for specific surface area obtained by analytical techniques were much larger than the ones obtained using the proposed methodology. The reason would be the effect of penetration of N_2 in the material associated with cell wall surfaces facing cell lumen region. A good fit between most of the estimated geometrical properties and reported experimental data was observed, meaning that their trend can be modeled. The study also shows that average values for the shape factor and sphericity, considering investigated fraction's sizes, are approximately constant or with little variation in relation to the characteristic dimension of the particles over the full range of size class. Therefore, these characteristics cannot be represented by simple linear or nonlinear models. The shape factors determined in this work were approximated through cubic expressions obtained by non-linear regression. It shows that most particles present shapes that are far from spherical.

Nomenclature

A_{s_i} Average surface area in the respective size class (mm^2)
A_s Actual surface area of the particle (mm^2)
$A_{s_{sphere}}$ Surface area of the sphere equivalent with the same volume of the particle (mm^2)
A_{proj} Projected area of a rectangular prism (mm^2)
$A_{p_{sphere}}$ Projection area of the sphere (mm^2)
A_p Projection area of the particle (mm^2)

Table 9
Empirical mathematical models for the approximation of geometrical properties of sugarcane trash particles.

Property	Symbol	Unit	Equation	R^2
Equivalent diameter	D_{eq}	mm	$D_{eq} = 1.0183X_i^{0.7618}$	0.9224
Projected area	A_p	cm^2	$A_{proj} = 0.0537X_i^{1.4694}$	0.9779
Transversal section area	$A_{stprism}$	cm^2	$A_{stprism} = 0.0018X_i^{1.6431}$	0.8664
Surface area	A_{sup}	cm^2	$A_s = 0.1612X_i^{1.4781}$	0.9721
Shape factor	ψ	–	$\psi = 0.4686 - 0.2125X_i + 0.0497X_i^2 - 0.0033X_i^3$	0.4508
Area shape factor	ψ_s	–	$\psi_s = 13.553e^{-0.1206X_i}$	0.8767
Volume shape factor	ψ_v	–	$\psi_v = 0.4381e^{-0.1662X_i}$	0.5868
Volume	V_p	cm^3	$V_p = 0.0006X_i^{2.2855}$	0.9224
Sphericity	φ	–	$\varphi = -0.0033X_i^3 + 0.0495X_i^2 - 0.2105X_i + 0.4136$	0.5077
Area shape factor to Volume shape factor Ratio	ψ_s/ψ_v	–	$\psi_s/\psi_v = -51.292 + 67.161X_i - 14.733X_i^2 + 0.951X_i^3$	0.5593

A_{stpris} Area of the transversal section of the particle (rectangular base prism) (mm^2)
D_{eq} Equivalent diameter (mm)
l, a, b Length, width and thickness of particle (mm)
$\bar{l}, \bar{a}, \bar{b}$ average Length, width and thickness of particle (mm)
$^l/_a$, $^l/_b$ e $^b/_a$ geometric relations (dimensionless)
m Mass parameter (g)
M Mass of the amounts of particles with Xcharacteristic dimension (g)
M_i Mass fraction parameter (dimensionless)
$\sum m_i$ Sum of mass of each particle studied (g)
$\bar{m}_p$ Average mass of the particle (g)
N Number of particles that has Xas a diameter (dimensionless)
q Area ratio (dimensionless)
r Prismoidal relation (dimensionless)
s_e Total specific surface area of the particles (mm^2/g)
s_{e_i} Total specific surface area in the respective size class (mm^2/g)
V_{p_i} Average volume of the particles in their respective size class (mm^3)
$\sum V_{pi}$ Sum of volume of each particle studied (mm^3)
V_p Volume of the particle (rectangular base prism) (mm^3)
$\bar{V}_p$ Average volume of the particle (rectangular base prism) (mm^3)
X Characteristic dimension parameter
X_i Characteristic dimension in the respective size class of the particles (mm)
X_1 Standard screen size that allows the fraction to pass (mm)
X_2 Standard screen size that retains the fraction (mm)

Subscripts or superscripts
e Specific
e_i Specific in the respective size class
eq Equivalent
i Individual particle or all particles in their respective size class
p Particle
$proj$ Projection of the rectangular prism
p_{sphere} Projection of the sphere
s Surface or area
$sphere$ Sphere parameter
$stpris$ Transversal section of the rectangular prism
v Volume
1 Screen size that allows the fraction of material to pass
2 Screen size that retains the fraction of material

Greek letters
ε Mean conglomerate porosity (dimensionless)
ρ_s Particle apparent density, kgm^{-3}
ρ_a Particles apparent density of each size class, kgm^{-3}
$\bar{\rho}_a$ Average particles apparent density of each size class, kgm^{-3}
φ Sphericity (dimensionless)
ψ Shape factor (dimensionless)
ψ_s Area shape factor (dimensionless)
ψ_v Volume shape factor (dimensionless)

Abbreviations
ABNT Associação Brasileira de Normas Técnicas
ASTM American Society for Testing and Materials
CTBE Laboratório Nacional de Ciência e Tecnologia do Bioetanol
IZ Instituto de Zootecnia
NREL National Renewable Energy Laboratory
PSD Particle Size Distribution
PSDA Particle Size Distribution Analysis
SSFT Simultaneous Saccharification and Fermentation Technology

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