

Chapter 2

Engineering Properties of Biomass

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Abstract Engineering properties of biomass are important for the design and operation of processing facilities for handling, storage, transportation, and conversion to fuels, heat, and power. These properties include bulk density, particle density, particle size, color, moisture content, ash content, heating value, and flowability. In this chapter, the characterization methods of these properties are reviewed. In particular, the recent development of the characterization techniques and progress in understanding these engineering properties of the biomass are discussed. The heterogeneous nature of biomass requires standardized characterization procedures and statistical models development to predict their physical properties for engineering design and operation.

2.1 Introduction

Lignocellulosic biomass sourced from plants is a renewable and sustainable natural resource that can be engineered into feedstock for producing heat, power and chemicals. Different parts of the plants have different microstructure and chemical

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compositions. For example, a wood log consists of stem wood (white wood) and bark. Stem wood has a lower ash content compared to the bark by tenfold. As a result, bark may not be an excellent fuel source for combustion to produce heat and power. Therefore, biomass has to be fractionated and engineered by biomass processing in order to extract the appropriate parts for particular end-user application.

Engineering properties of biomass are those that control the way biomass is prepared for either its handling or its conversion to other forms. These properties can be divided into structural, compositional, thermal, and electromagnetic properties. Structural properties may manifest themselves in the form of mechanical and physical properties. Compositional properties are chemical constituents of the biomass. Thermal properties relate to heating and cooling rates and heat transfer between the material and its environment as well as the calorific value of biomass. Electromagnetic properties relate to the response of the material when exposed to waves from electromagnetic spectra. These four properties are highly interrelated, i.e., the change in one influences a change in the others. These material properties can be studied separately, keeping in mind that their unavoidable interactions are important.

Considerable research has been conducted on agricultural and forest material properties over the last 50 years. Much of these properties can be extended and applied to biomass. Professor Mohsenin of Penn State University was first to collect and publish the state of the art in definitions and measurements of thermal [1], electromagnetic [2], and physical properties [3] of agricultural material. Since then, numerous books and articles have been published on the properties of foods [4, 5] and woody products [6]. More recently, methods of evaluating the compositional properties of biomass were presented [7]. The ASABE Book of Standards maintains updated properties for agricultural and forest materials. Similarly, International Organization for Standardization (ISO) is in the process of establishing procedures for biomass properties characterization.

Energy providers are including bioenergy in their portfolio as the demands for energy are increasing and the known petroleum resources are dwindling. Environmental concerns with burning coal are shifting attention to biomass as an alternate solid fuel [8]. Conversion processes, whether they are simply converting biomass to heat and power or involve more complex biomass to gaseous or liquid fuels conversions, require high-quality and cost-competitive feedstock [9]. Simple combustion may utilize feedstock with a wide range of moisture contents, mixtures of species bark and stem wood, and a wide range of sizes and ash content. The more complex processes such as chemical or enzymatic hydrolysis require feedstocks with close tolerances in particle size and density [10]. Meeting tight specifications can be challenging as forest feedstocks are highly variable in many of the relevant physical and chemical compositions. The source of the feedstock will have direct impact on the available quantities of biomass and the cost of harvesting and logistics. Understanding these characteristics is an important element in ensuring that new investments in bio-industry match the available feedstock supplies.

The engineering properties of biomass highly affect the quality of feedstock for densification and eventually their use in either biorefinery or in a combustion application. These properties include density, particle size, flowability, moisture

Table 2.1 Engineering properties of biomass

Engineering properties	Engineering application	Characterization methods/standards/reference
Density	Supply logistics, transportation, and storage of biomass in different forms: chips, logs, ground particles and pellets, etc.	[17, 18]
Particle size	Design parameter for efficient downstream conversion	[19–22, 26]
Angle of repose	Design parameter for handling and storage facilities	[27–31]
Moisture content	Design parameter for drying and thermal conversion processes	[38, 39]
Calorific value	Energy recovery efficiency	[40–45]
Ash content	Estimation of the potential risk of slagging and fouling issues during biomass combustion/gasification	[47, 48]
Color	Quality control and a quick estimation of fuel properties (e.g., heating value)	[42, 49]

content, heating value, ash content, and color, which are all important engineering properties for the design and operation of the downstream biochemical process. They also highly affect the design of handling and transportation systems, storage in hoppers and silos, and fuel conversion equipment [11, 12].

In the following sections, we discuss the typical characterization method of the physical properties of the biomass (Table 2.1) and also review recent progress in understanding their engineering properties.

2.2 Characterization Methods of Biomass Engineering Properties

2.2.1 Density

Density of a biomass is defined as the mass over its volume (kg/m^3 or lb/ft^3). In the context of bioenergy, we divide density into two groups: bulk density and particle density.

2.2.1.1 Bulk Density

Bulk density is an important characteristic of biomass that influences directly the cost of feedstock delivered to a biorefinery and storage area [13–15]. The non-uniform particle size and shape of the raw biomass including leaves and stems lead to the high cost for transportation, storage, and feeding of the particles into each unit operation. The standardization of the characterization method of the bulk density of biomass for logistic optimization is of utmost importance (Fig. 2.1).

Fig. 2.1 A container filled with 14.7-mm switchgrass particles for bulk density measurement. Reprinted with permission from Lam PS, Sokhansanj S, Bi X, Lim CJ, Naimi LJ, Hoque M, Mani S, Womac AR, Narayan S, and Ye XP. 2008. Bulk density of wet and dry wheat straw and switchgrass particles. *Applied Engineering in Agriculture* 24(3): 351–358. St. Joseph, Mich.: ASABE



Bulk density measurement of the biomass powder or large particles can be performed according to the method of ASTM D1895B [17] or ASABE S269.5 OCT2012 [18]. For the biomass ground particles (i.e., less than 2 mm in diameter), a container with a volume of 0.615 L was used, above which a funnel with the opening diameter of 1.5 cm was suspended. The funnel was then filled with the biomass grinds and they were allowed to flow freely into the circular container from a height of 20 cm. The biomass grinds were stirred continuously by a thin metal wire throughout the pouring operation to prevent clogging inside the funnel opening. The excess material on top of the container was scraped off with a straight edge. The container with sample was weighed and weight/volume (loose bulk density) was determined. For tapped density, the loosely filled container was tapped on the laboratory bench five times in a vertical direction. The weight of the filled container was recorded after five tappings.

ASABE 269.5 [18] states that for all densified products (cubes, pellets, or crumbles), use a cylindrical container with a height-diameter ratio within the range of 1.25–1.50. The diameter of the container must be at least ten times larger than the largest dimension of a single product. The container is filled by pouring from a height of 2 ft (610 mm) above the top edge of the container. The container is to be then dropped five times from a height of 150 mm onto a hard surface to allow settling. In the case of small pellets and crumbles, the material shall be struck off level with the top surface. More materials may need to be added after settling to fill the container. In the case of cubes and large pellets, remove products which have more than one-half their volume above the top edge of the container, leaving in the container those products with more than one-half of their volume below the top edge of

the container. As the tendency of densified products tend to expand for some time after forming, both the time interval between forming and the moisture content during the measurement should be specified. Bulk density measurements should be repeated at least five times, and the average value and the range must be reported. Bulk density of a biomass varies with its moisture content and particle size. Therefore, the bulk density of a measured product should be specified with moisture content and particle size and shape. Information on shape and geometry of particle size is also important.

2.2.1.2 Particle Density

Particle density is the mass of an individual particle over its volume. For a group of particles, the particle density is the mass of all particles divided by the volume of the particles occupying excluding the pore space volume. For a particle that can be defined accurately geometrically, the mass of a single particle is measured using a digital caliper. For example, a wood pellet can be geometrically defined as a cylinder. The ends of the wood pellets are flattened with sandpaper to make them exact cylinders. The length (L) and diameter (D) of the pellets are measured with a caliper. The apparent volume is calculated by (2.1):

$$V = \frac{\pi}{4} D^2 L \quad (2.1)$$

For particles that cannot be defined geometrically, indirect methods are used. For example, wood pellet density is calculated by measuring the volume of two to three wood pellets with a Quantachrome Multipycnometer (Quantachrome, Boyton Beach, FL, USA). Nitrogen is injected into void spaces of the biomass. The pressure difference with a known quantity of pressurized nitrogen flows from a reference volume into a cell containing samples is used to determine biomass particle true volume. The volume of the particle is calculated from an ideal gas law equation (2.2). The volume measurements of particle must be repeated three times for each sample for determination of an average volume.

$$V_p = V_c - V_R \left[\frac{P_1}{P_2} - 1 \right] \quad (2.2)$$

where V_p is the volume of biomass particles (cm^3), V_c is the sample cell volume (cm^3), V_R is the reference volume (cm^3), P_1 is the pressure reading after pressurizing the reference volume (Pa), and P_2 is the pressure reading after including V_c (Pa). The density is the ratio of mass of pellets over the measured volume (2.3).

$$\rho_p = \frac{m}{V_p} \quad (2.3)$$

Interparticle porosity provides the packing information of the biomass particles inside a known container and is determined by (2.4).

$$\varepsilon = 1 - \frac{\rho_b}{\rho_p} \quad (2.4)$$

where ε is the porosity, ρ_b =bulk density of biomass grinds (kg/m^3), and ρ_p =particle density of biomass particle (kg/m^3).

For large pieces that do not fit into a pycnometer cell, the method of immersion in water is recommended [18]. A few representatives of samples are selected and their mass are weighed, W_1 . The empty container is initially filled with two-thirds of water and the scale is set to zero. The container must be transparent, and its diameter must be large enough to accommodate the piece in a plastic bag. Each piece of sample is placed in a plastic bag with the breadth of 0.03 mm. A thin metal rod with a ring at the other end was used to push the piece into the water. The mass was recorded from the scale, W_2 . Another check was performed by checking the sample piece absorbing through a bag with leak with W_1 . The density is calculated from (2.5).

$$SW_1 = \left(\frac{W_1}{W_2 - W_3} \right) \quad (2.5)$$

where SW_1 =particle density of test piece (kg/m^3), W_1 =piece mass in air (kg), W_2 =mass of water displaced by the piece, bag, and rod (kg); and W_3 =mass of water displaced by bag and rod, without the sample piece, when they are immersed to the depth at which W_2 reading was taken (kg).

ASABE 269.5 specifies that W_3 should be further corrected by subtracting a small value, for example, 7 g, to compensate for error in the fit of the bag to the piece.

For pieces of irregular shape, the following procedure may be used: Insert a thin metal rod into the piece and immerse the piece into molten wax such that a thin film covers the surface area. Allow the wax-covered piece to cool, and then follow the procedure outlined above to determine the particle density. The particle density measured above will then be corrected to 0 % moisture content by (2.6):

$$SW_c = SW_i \frac{\%DM}{100} \quad (2.6)$$

where SW_c =particle density at 0 % moisture content (kg/m^3), SW_i =measured particle density (kg/m^3), and %DM=percent dry matter in test particle.

Particle density calculation does not make any allowance for shrinkage or expansion that may occur during a potential drying process. Measurements should be done on at least five samples and the average, range, and number of samples reported. Because of a tendency for pieces to expand for some time after forming, both the time interval between forming and the measurement and the moisture content at the time of this measurement should be specified.

2.2.2 Particle Size

Woody biomass and herbaceous crops are of irregular shapes. Some are of a needle form with high an aspect ratio (length divided by diameter) and the finely ground particles have a round shape with an aspect ratio close to one. The range of the particle size of woody biomass is huge, from spanning wood logs to ground powders after milling. For herbaceous crops, the particles include leaves and stalks which are fluffy in nature [16]. There are three dimensions for these particles, including particle length, width, and thickness. However, some of the traditional particle size measurement techniques, e.g., sieving, are limited to the measurement of one single dimension of the fibrous particles (e.g., particle width) only. In addition, a long piece may actually pass through a sieve because it is oriented perpendicular to the sieve and therefore passing through due to small width/thickness. This makes the exact dimension measurement difficult and challenging. Therefore, there is a strong need to develop accurate characterization techniques for biomass particle size and shape for designing the handling, storage, and processing units including chemical reactors for treatment. Sieve analysis and digital imaging techniques are two major characterization methods for particle size analysis.

2.2.2.1 Sieve Analysis

A particle size analysis of biomass ground particles using sieves with square holes opening was studied [19]. Prior to sieving analysis, samples were conditioned to consistent low moisture content (e.g., 10 % moisture content [w.b.]) at a drying temperature of 50 °C. This conditioning ensures that the particles do not stick to each other by capillary force of moisture during sieving process. Particle size distributions were determined according to the ASABE Standard S319.4 JUL97 [20], using a Ro-Tap sieve shaker (Tyler Industrial Products, OH, USA). A sample of approximately 20 g wheat straw, switchgrass, and corn stover grinds was placed on top of a stack of sieves, arranged from the smallest to the largest mesh number. Sieves used for 1.6-mm (1/16") samples were 18, 25, 35, 45, 60, 80, 100, 120, 170, and 230, corresponding to nominal sieve openings of 1.00, 0.707, 0.500, 0.354, 0.250, 0.177, 0.149, 0.125, 0.088, and 0.063 mm [19]. Sieving time was 5 min for each sample. The mass retained on each sieve was weighed to obtain the particle size distribution of the biomass. The geometric mean diameter (d_{gw}) of the sample and geometric standard deviation of particle diameter (S_{gw}) were calculated accordingly.

To verify the characteristics of particles retained on each sieve, a representative sample of particles from each sieve was selected. The length and the maximum diameter of the particles belonging to each sample were measured with a caliper. It is known that the sieve opening is not a representative of particle length, but it is a representative of the particle maximum diameter. However, this relationship is weakened as particles size increases.

Different methods of size classification of wood chips were discussed by Hartmann et al. [21]. He mentioned that screens are common in wood classification.

Table 2.2 Dimensions of circular hole sieves

Screen No.	Hole diameter (mm)	Screen thickness (mm)	Open area (%)
1	48	26.0	35.98
2	32	20.0	33.00
3	16	9.53	35.65
4	8	6.35	32.45
5	4	3.00	32.77
Pan			

Because of the mentioned problem associated with long and thin particles, the application of a dynamic online image analysis can improve its effectiveness. This new classification method can sort particles based on more than one dimension, but it has the problem of particles overlapping. So, the most reliable method of characterizing the size of particles is still direct measurement of size by hand, using a digital caliper.

ASABE S424 specifies the use of a stack of thick plates with square holes to analyze the size of cut forages in the field [22]. The thickness of the plates is proportional to the dimension of the hole. Larger holes have a thicker dimension and this makes sure the long particles do not have enough space to pass through the holes during sieving. A biomass sieving system was developed at the University of British Columbia (UBC), Vancouver, based on the ASABE 424 standard. The sieving system consists of a stack of five round sieves plus pan. Each sieve has a height of 85 mm and a diameter of 305 mm except the sieve with the smallest hole that has a height of 4 mm and rests on a pan with the height of 45 mm. The dimensions of each sieve are summarized in Table 2.2.

The sieve shaker (Retsch Model AS 400, Newton, PA) applies a horizontal circular motion. The speed ranges from 50 to 300 rpm and can be electronically controlled. The actual value of the number of revolutions is digitally displayed.

2.2.2.2 Digital Imaging Technique

Digital imaging technique provides an accurate measurement of particle size by processing the particle's projected area in the image and counting the digital pixels with a preset of scanning resolution [20, 23–26]. The images can be taken either by a scanner or by a scanning electron microscope (Fig. 2.2). For the digital scanning method [26], the sample of ground fir softwood particle's images were taken by a CanoScan 4,400 F high-resolution scanner (Canon, Lake Success, NY). The resolution of the image was determined by the number of pixels per inch (DPI). The particles were scattered on a transparent plastic sheet before images were taken by the scanner. Prior to imaging, the individual particles were deliberately separated so that they did not touch or overlap with each other, which would affect the particle size analysis results. This manual separation of the particles was performed with the aid of a magnifying glass. The resulting images were analyzed with MATLAB software



Fig. 2.2 Cross-sectional surface of switchgrass ground particles under scanning electron microscope

(The MathWorks Inc., Natick, MA) using an image processing and statistical toolbox. The particle length and particle width were defined as an ellipsoidal major axis and ellipsoidal minor axis measured by the MATLAB imaging toolbox. These two major parameters were used in the toolbox to calculate individual particle's equivalent spherical diameter and aspect ratio. The number of particles, particle length, particle width, and aspect ratio was reported. For each studied particle, three imaging replicates were measured and averages reported.

2.2.3 Flowability

Static angle of repose is a flowability indicator of the material, which is a function of particle shape, friction, and cohesiveness. It is defined as the angle at which a material will rest on a stationary heap. It also helps to design the loading height and the pile dimensions of the biomass particles [27–31].

Flowability of biomass grinds can be determined by the angle of repose test using a Mark 4 version tester developed by Geldart (Powder Research Ltd., UK). The sample flowability is generally classified as free flowing, fair flowing, and cohesive [32]. A flowability study of ground particles of wheat straw, switchgrass, and corn stover was studied using the Mark 4 version tester [19]. Twenty-five grams of biomass grinds collected on each mesh after sieving is slowly poured onto the uppermost stage with the vibrating chute [19]. The vibratory chute was shaken

constantly in order to make sure the samples poured continuously and smoothly into the funnel. The samples will flow through the funnel and form a heap with a conical shape. Measurement of height (H) and radius (R) of the rest particles was taken five times to determine the average value of angle of repose.

The height and radius of the semi-cone were measured and the angle of repose (α) was calculated from (2.7):

$$\alpha = \tan^{-1} \left(\frac{H}{R} \right) \quad (2.7)$$

where α is the static angle of repose (degree), H is the height (cm), and R is the radius (cm).

2.2.4 Moisture Content

Moisture content of biomass is one of the important physical properties for the design of a drying process [33]. Woody biomass is usually wet when collected from the forest. It must be dried and processed to produce feedstock for heat and power and chemical production. Dried biomass is also preferred during handling and storage to minimize the mold formation [34], off-gassing [35], and self-heating issues [36, 37]. Drying kinetics of biomass for the dryer design is usually determined by the accurate measurements of the moisture content of the biomass at different intervals.

One of the standardized moisture content measurement methods for biomass is described in the ASABE Standard S358.2 [38]. The procedure involves weighing and drying about 100 g of pieces of biomass as received, in triplicate in a forced air convection oven at 103 °C for 24 h to obtain the completely dry biomass. The dried samples are cooled and weighed. A digital balance with 0.01-g precision is used for the weighing procedure. The developed ISO standards are based on European standard CEN/TS 14774-3, which specifies 105 °C for 60 min for determination of moisture content for solid biofuels [39]. The required mass of the small particles with 1-mm geometric mean diameter is a few grams, while that for the large particles (e.g., wood chips) is 500 g.

2.2.5 Calorific Value

Calorific value of biomass is crucial to determine its energy that can be recovered during thermo-conversion. From recent studies, it was found that thermally treated biomass with increased calorific value could be a suitable candidate to blend and co-fire with coal for power generation with reduced greenhouse gas emissions [40–45].

Calorific value of each biomass sample can be measured by a Parr calorimeter model 6300 (Parr Instrument Company, Moline, IL). A sample consisting of 40 g was ground in a knife mill through a 2-mm screen. Approximately 1 g of the ground particles was weighed. A pellet was made from the ground particles using the manually operated Parr Pellet Press. The weight of the pellet was entered as an input data to the calorimeter. The pellet was placed in a crucible immersed in a bucket filled with 1 L of distilled water. The bucket was placed in the calorimeter. The calorific value of the pellet was recorded as the high heat value (HHV) in MJ per kg of dry biomass.

2.2.6 Ash Content

Biomass ash causes lots of operational problems during biomass processing, combustion, and emissions. For example, silicon of biomass ash is the main contributor to wear out of the blades of the size reduction unit [46]. Potassium and calcium cause fouling of heat exchangers and slagging in the bottom of the furnace. These require shutting down the units regularly, reducing the operating time of the production units, and also increasing the maintenance cost. Therefore, the quantitative analysis of biomass's ash content is critical for process design. Sometimes, a leaching pretreatment process is required to extract the ash from the biomass before the downstream processing. This helps to facilitate an efficient and economical downstream process with a high-quality product yield.

Ash content of the oven-dried biomass was measured using the NREL/TP-510-42622 procedure [47]. A sample of softwood chips consisting of 40 g was ground in a knife mill through a 2-mm screen. Three replicates of 0.5–0.8 g of each ground sample were placed inside a muffle furnace equipped with a thermostat. The temperature control for the furnace was set at 575 °C furnace based on the suggested temperature program. At the end of the test, the ash sample was placed in a desiccator to cool. The final weight of the sample was measured and recorded. Ash content was expressed on a dry mass basis. The ash compositional analysis can be done by EDAX or ICP-MS [48].

2.2.7 Color

Color is an important attribute of the biomass. For the biomass without thermal treatment, a sample with dark color is usually correlated to high ash content. For example, the pellets made with bark are darker in color [42]. For the biomass with thermal pretreatment, the degree of the darkness of the sample can be highly correlated to their degree of thermal treatment (e.g., torrefaction and steam explosion [49]), as well as to the calorific value of the biomass.

The color of the biomass particle with different degrees of thermal pretreatment was measured using a color spectrophotometer (Konica Minolta CM-5, Osaka,

Japan) [42, 49]. The black and white calibrations were performed before the reflectance measurement. All measurements were made using an observer angle of 10° and a D65 illuminant. The 0 % color was calibrated with black and 100 % with white standards. A sample of ground particle was spread out inside a Petri dish as recommended by the instrument's operator manual. The color coordinates L^* , a^* , and b^* (lightness, redness/greenness, and yellowness/blueness) were determined for each sample. Five replicates of measurement were carried out.

The variation in color coordinates was calculated as the difference between the measured values for L^* , a^* , and b^* coordinates for the untreated and treated wood. The differences were expressed in percentage of the initial value,

$$\Delta L^* = 100 \frac{(L_{treated}^* - L_{untreated}^*)}{L_{untreated}^*} \quad (2.8)$$

$$\Delta a^* = 100 \frac{(a_{treated}^* - a_{untreated}^*)}{a_{untreated}^*} \quad (2.9)$$

$$\Delta b^* = 100 \frac{(b_{treated}^* - b_{untreated}^*)}{b_{untreated}^*} \quad (2.10)$$

2.3 Recent Progress in Analyzing Biomass Engineering Properties

2.3.1 Bulk Density, Particle Size, and Flowability

The bulk density and flowability of the biomass particles are highly influenced by the particle size and shape. In most studies, the bulk density of a mixture of ground particles from different sieves was measured [19, 50–53]. Mani et al. (2004) reported that the bulk and specific densities increase with the geometric particle diameter of the particles at the same moisture content and developed second- or third-order polynomial models relating the bulk and specific densities of agricultural biomass grinds to their respective geometric particle diameter of the biomass grinds within the range of 0.18–1.43 mm [50].

Sone's model was used to understand the compaction characteristics by tapping of different biomass [51], and it was found that the chopped wheat straw particles compacted very rapidly to reach the final tapped density as compared to the chopped switchgrass and corn stover particles [52]. This result may be due to the low value of Hausner ratio (i.e., the ratio of tapped density over the initial bulk density) of chopped wheat straw particles and also its better flowability than the chopped switchgrass and chopped corn stover. Tapping motion causes the particles to move to each other to fill up the bulk pores in between the particles and rearrange their

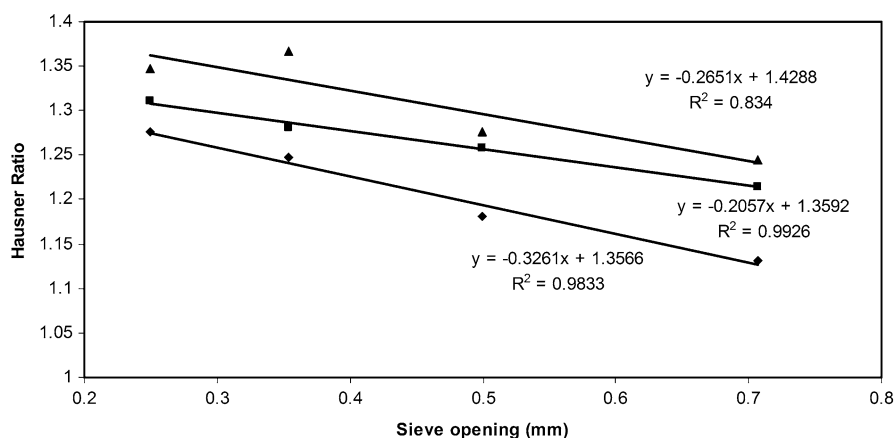


Fig. 2.3 Hausner ratio of biomass grinds at different particle sizes (*filled diamond*: switchgrass; *filled square*: corn stover; *filled triangle*: wheat straw)

packing structure to a more compacted form. Normally, a low Hausner ratio indicates that the initial bulk density of the packed particles after loading is already quite close to the tapped density. Those packed particles required fewer number of tapping to rearrange the particle packing structure in order to reach the final tapped density. The particles with poor flowability will limit the tendency of the packed particles to rearrange their pack structure to achieve a closer packing caused by tapping. For example, the particles with a rougher surface may increase the internal friction between the particles and thereby limit the particles to move to fill up the bulk pores.

When the biomass particles were further fractionated into individual particle fractions and their individual bulk density was measured [19], the bulk density of the switchgrass and wheat straw stem particles increased with decreasing particle length and the bulk density of the switchgrass and wheat straw stems increased by 10–50 % due to tapping. Switchgrass achieved lower Hausner ratio than corn stover and wheat straw for different particle sizes between 0.25 and 0.71 mm (Fig. 2.3). It was observed that the switchgrass particles flowed into the container relatively faster than wheat straw and corn stover, and hence, the initial bulk porosity was the lowest. Upon tapping, switchgrass particles had less space to fill up the interspace voids and the bulk density increased slightly to reach the final tapped density.

The flowability of the biomass grinds with the same particle sizes was different by the results of the angle of repose [19]. This difference in flowability was attributed to different particle shapes and the forces between the particles. The moisture content of wheat straw, switchgrass, and corn stover after grinding was roughly between 5.1 and 8.7 % in this study. This suggests the capillary force acting on those biomass particles is within a close range, and moisture content did not show much effect on the cohesiveness of the grinds. Nzokou et al. (2005) report that lignin and extractive content on the wood surface affects the wettability and the Van der Waal's force between the particles [54]. It may further help to explain the effect of lignin and extractives content on different biomass flowability.

Table 2.3 Flowability chart of different agricultural biomass ground particles at different particle sizes; parenthesis shows the standard deviation with $n=5$

Species	Switchgrass		Wheat straw		Corn stover	
Sieve opening (mm)	Angle of repose	Types of powder	Angle of repose	Types of powder	Angle of repose	Types of powder
0.707	35.56 (1.21)	Free flowing	43.05 (2.00)	Fair flow	43.57 (1.23)	Fair flow
0.5	38.60 (1.15)	Free flowing	45.80 (2.60)	Cohesive	45.40 (1.37)	Cohesive
0.354	39.82 (0.48)	Fair flow	47.53 (1.87)	Cohesive	45.64 (0.73)	Cohesive
0.25	43.03 (0.23)	Fair flow	47.44 (1.61)	Cohesive	46.12 (0.55)	Cohesive

Table 2.3 shows that corn stover and wheat straw have fair flowability at the largest particle size, while switchgrass shows the best overall free-flowing characteristics for all the particle sizes. The angle of repose of wheat straw and corn stover increases from 43° to 47° with decreasing particle size. The angle of repose of switchgrass increases from 36° to 43° with decreasing particle size. The classification of the powder type for the biomass grinds is based on the measured angle of repose [32]. Wheat straw and corn stover with particle size of 0.707 mm change from fair flow to cohesive with decreasing particle size of 0.25 mm. Switchgrass particles exhibit a free-flowing behavior for the particles with sizes of 0.5–0.707 mm, and the smaller particles with particle sizes of 0.25–0.354 mm have fair flow characteristics. These results should be due to difference in forces existing on the surfaces between the inter-particles.

2.3.2 Color, Moisture Content, and Calorific Value

The color and calorific value of untreated and thermally treated biomass can be correlated. For example, it was known that the calorific value of thermally treated biomass increases with the darkness (Fig. 2.4). For industries, development of efficient characterization tools using color as a parameter would benefit them in grading different products. For example, when the power generation utilities would like to check the fuel quality of each million ton batch of delivered biomass, they may prefer to have a quick fuel properties measurement instead of sending off many small randomly selected samples to the certified laboratory for fuel properties measurement (e.g., calorific value, moisture content, and hydrophobicity). As a result, the development of new characterization protocols and standards is needed to support the growth of the use of biomass for energy production.

Our recent work reported that a simple color measurement can quickly estimate the calorific value of the thermally treated biomass using the statistical multi-linear models [49]. It showed that correlation among color coordinates and compositional properties of treated biomass is strong and could potentially lead to the development of reliable instruments (Table 2.4). The typical multi-linear regression (MLR) was used to model responses of the three color components, i.e., L^* (whiteness or

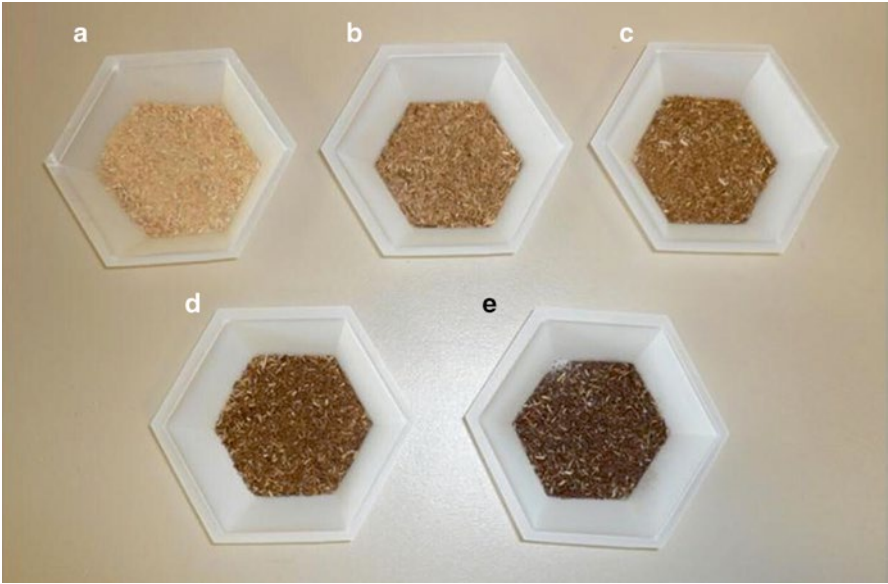


Fig. 2.4 Physical appearance of steam-exploded particles treated at different steam explosion conditions. From *left to right*: (a) untreated Douglas Fir; (b) 200°C, 5 min; (c) 200°C, 10 min; (d) 220°C, 5 min; (e) 220°C, 10 min. Reprinted with permission from Lam PS, Sokhansanj S, Bi XT, and Lim CJ.2012. Colorimetry applied to steam-treated biomass and pellets made from western Douglas fir (*Pseudotsuga menziesii* L.). *Transactions of the ASABE* 55(2): 673–678. St. Joseph, Mich.: ASABE

Table 2.4 Multi-linear regression equations (MLR) between color parameters, chemical composition, and elemental composition ($\alpha=0.01$, number of replications = 2)^a

	Equation parameters						
Dependent variable	Intercept	L^*	a^*	b^*	R^2	F -Value	p -Value
Elemental analysis with color parameter							
C	12.1038	1.2117	7.2308	−4.0882	0.97	261.06	<0.0001
H	0.0709	0.2654	1.602	−0.911	0.99	1093.07	<0.0001
O	−0.8498	0.0633	0.3755	−0.212	0.97	258.9	<0.0001
Chemical composition with color parameters							
Lignin	−252.71	8.5533	48.5518	−27.0467	0.97	210.67	<0.0001
Extractives	48.244	−0.6582	−3.7874	1.0474	0.99	660.38	<0.0001

^aReprinted with permission from Lam PS, Sokhansanj S, Bi XT, and Lim CJ.2012. Colorimetry applied to steam-treated biomass and pellets made from western Douglas fir (*Pseudotsuga menziesii* L.). *Transactions of the ASABE* 55(2): 673–678. St. Joseph, Mich.: ASABE

lightness), a^* (redness or greenness), and b^* (yellowness or blueness). MLR models were created from range-scaled factors of elemental composition, i.e., percentages of C and H of the untreated and steam-treated samples at different treatment temperature and time. By the use of range-scaled factors, differences in magnitude in

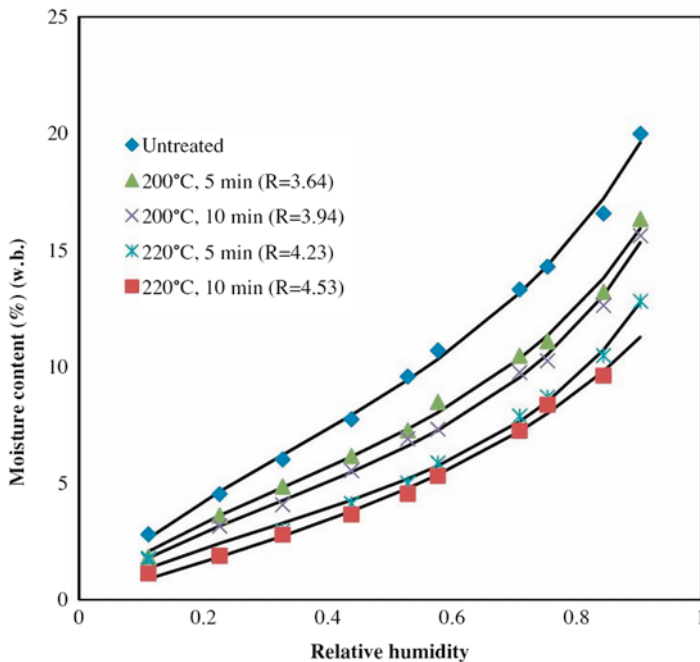


Fig. 2.5 Moisture sorption isotherms for untreated Douglas fir particles and steam-treated particles at different temperature and treatment time (solid lines show GAB model). Reprinted from Bioresource Technology, 116, Lam PS, Sokhansanj S, Bi XT, Jim Lim C, Larsson SH, Drying characteristics and equilibrium moisture content of steam-treated Douglas fir (*Pseudotsuga menziesii* L.), 7, Copyright 2012, with permission from Elsevier

the factors were extinguished when values were recalculated to range from -1 to $+1$. Thus, the sign of the modeled coefficients showed if the factors were negatively or positively correlated to the response. The magnitude of the modeled coefficients was equivalent to the impact that each factor had on the response. The MLR models were studied in the range between $200\text{ }^{\circ}\text{C}$, 5 min and $220\text{ }^{\circ}\text{C}$, 10 min:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \dots + \beta_p x_{ip} + \varepsilon_i$$

for $i = 1, 2, \dots, n$

(2.11)

where y_i are the measured responses, β_i are the estimated parameters of the population regression line x_i , p represents the independent variable of the i th measurement, and ε_i is the model deviation. Further research in this area will develop data on color versus material properties for a range of feedstock at varying moisture content, which appears to be a major confounding factor.

Apart from the correlation of color and calorific value, our recent research findings developed an equilibrium moisture content (EMC) database for steam-treated woody biomass both in ground particles and pellets [33]. It was found that the EMC of steam-treated samples decreased with increasing treatment temperature and time (Fig. 2.5). The Guggenheim-Anderson-de Boer (GAB) equilibrium model gave a

close fit with the data with $R^2=0.99$. Up to now, there is a comprehensive database of moisture sorption database for woody biomass in the USDA handbook [55]. However, there is a lack of moisture sorption database for the thermally treated biomass at different severities (e.g., temperature and time) and using different thermal treatment methods. Future work should focus on the development of the moisture sorption database of thermally treated biomass to optimize the design of handling, storage, drying, grinding, pelletizing, and conversion units.

2.4 Summary

Biomass is a natural resource that exhibits heterogeneity in structure and chemical composition. A deep understanding of biomass physical properties and fast tools for characterizing these properties are required for the design and safe operation of processing facilities. Recent research on bulk density, particle size, and flowability of biomass particle showed that traditional sieve analysis cannot cover the measurement of all three dimensions of the particles and thereby could not correlate well with the packing and flowability data. Digital imaging techniques seem to be an advanced solution to capture more information from projected areas in all three dimensions. Fuel properties of lignocellulosic biomass could be quickly determined by a simple color measurement. The moisture sorption database of thermally treated lignocellulosic biomass is under development, and it will be highly useful and of interest to the power generation companies to replace coal with biomass as fuel for power generation.

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