Waste Biomass Valor (2018) 9:853–859
DOI 10.1007/s12649-017-9835-y

ORIGINAL PAPER

The Characteristics of Shredded Straw and Hay Biomass—Part 1—Whole Mixture

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Received: 4 March 2016 / Accepted: 17 January 2017 / Published online: 8 February 2017

Abstract The aim of this study was to determine the characteristics of shredded biomass from hay, straw and their mix in the ratio 1:1 using a sieve separator with oscillatory motion in the horizontal plane. The research was carried out according to the method described in ANSI/ASAE S424.1 standard. It was found that the geometric mean value of particle sizes x_g of shredded biomass from hay, straw and their mix of dimension: 3.45, 3.21 and 2.14 mm, respectively, the greatest impact had the smallest fraction, considered to 10th percentile of cumulative weight distribution x_{10} with dimensions 0.32, 0.21 and 0.06 mm, respectively. For hay, straw and mix mass relative span RS_m of fines was 3.51, 4.02 and 6.19, respectively, and was negatively correlated with the distribution uniformity index I_u. That was confirmed by lower values of graphic kurtosis K_g, inclusive graphic skewness GS_i and coefficient of uniformity C_u, which correlated positively with the coefficient of gradation C_g and distribution geometric standard deviation of the high GSD_1, low GSD_2 and total GSD_{12} regions distributions. All of biomass particles size distributions belonged to "very poorly sorted" category and were "very fine skewed" and "leptokurtic". Determine the suitability of the material on the basis of particle size distribution parameters for pressure agglomeration process is an invaluable practical application of this research. It was stated that mix of hay and straw is a preferable material for making pellets according to its better fragmentation. However it is less homogenous as a result of high share of fine particles at dimension under 1.65 mm. The particle size distribution of finest particles should be verified.

Keywords Biomass · Distribution · Particle size · Whole mixture

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Introduction

Biomass size reduction process changes the particle size and shape, increases bulk density, improves flow-properties, increases porosity, and generates new surface area [1, 2]. Mani et al. [3] report that the particle size has influence on the mechanical properties of the pellets of straw from wheat, barley and corn.

The particle size distribution measurement is generally carried out by mechanical sieving utilizing a standard sieve set, which is considered as a standard procedure [4–7]. Results from particle size distribution analysis include percentage of particles retained on different sized sieves, cumulative undersize distribution, arithmetic and geometric mean dimension and associated standard deviation, and several other parameters that uniquely describe the particle size distribution [1, 6–11] and effect on the physical properties of the material used in further transformation.

The analysis of the issue shows that there are known requirements for the characteristics of the particle size distribution of material from the remains of trees and the products produced from them (briquettes, pellets). This also applies to feed granules produced from shredded plant material [12]. Even greater experience was gathered in the field of pressure agglomeration of powders for making tablets. Results of research on agricultural biomass are fragmented and explanations in the available literature are not sufficient to evaluate the fragmentation of the material. It is very important for designing handling devices and for pressure agglomeration process. Understanding the roles of particle size distribution parameters will help in better design formulation or to develop appropriate characteristics that can give improved efficiency of suitability preparation of agglomerated materials.

The aim of the study was to determine the characteristics of shredded biomass from hay, straw and their mix using a sieve separator with oscillatory motion in the horizontal plane.

Materials and Methods

For tests the biomass chopped in the forage harvester with a theoretical cutting length of 2 mm were used. The shredded material from straw, hay and mix at a mass ratio of 1:1 had a moisture 6.44 ± 0.07, 7.58 ± 0.08, and 7.96 ± 0.08%, respectively.

Plant material moisture content was carried out by drying-weighting method according to the ASAE S358.2 standard [13].

Using sieve separator (set of sieves from the below: span, dimensions of opening screens in the sequence:1.65, 5.61, 8.98, 18 and 26.9 mm) with oscillatory motion in horizontal plane, chopped biomass were separated according to the standard of ANSI/ASAE S424.1 [5]. Each sample was sieved 5 times.

For the purpose of the distribution geometric mean of particle length $x_{g,}$ dimensionless standard deviation s_g and dimensional standard deviation s_{gw} were determined from the following relations:

$$x_g = \log^{-1}\left[\sum \left(m_i \log x_{si}\right) \Big/ \sum m_i\right] \quad (1)$$

$$S_g = \log^{-1}\sqrt{\sum \left(m_i \left(\log x_{si} - \log x_g\right)^2\right) \Big/ \sum m_i} \quad (2)$$

$$s_{gw} = 0.5 x_g \left[\log^{-1} s_g - \left(\log^{-1} s_g\right)^{-1}\right] \quad (3)$$

where x_g is the geometric mean of biomass particle size, mm; s_g is the standard deviation, dimensionless; s_{gw} is the standard deviation, mm; m_i is the mass of the material on the i-th sieve, g and x_{si} is the geometric mean of particle length on the i-th sieve determined from the formula:

$$x_{si} = \sqrt{x_i x_{i-1}} \quad (4)$$

where x_i is the holes diagonal of i-th sieve, mm and $x_{(i-1)}$ is the diagonal of sieve hole which is above the i-th sieve, mm.

The data of percentage part of cumulative undersize mass obtained from the sieve analysis are shown by a regression equation, using the equation of the Rosin–Rammler distribution [14] in the following form:

$$Y = 1 - \exp\left(-\left(x/x_R\right)^n\right) \quad (5)$$

where Y is the part of mass material, finer than size x; x is the particle size, receiving from the equivalent diagonal sieve opening, mm; x_R is the constant determining the size of the particles, mm and n is the constant characterizing material, which is a measure of the steepness of the curve distribution (dimensionless).

Dimensions of significance based on length and their distribution were derived from the cumulative undersize characteristics of particle dimensions original data. The following are several common particle size distribution parameters based on length were evaluated from these significant dimensions [6–8, 10, 15–17].

$$I_u = 100 \exp(-3.80423/n) \quad (6)$$

$$N_{sg} = 100 x_R \exp(-0.366513/n) = 100 x_R (0.69314718)^{1/n} \quad (7)$$

$$RS_m = \left(x_{90} - x_{10}\right)/x_{50} \quad (8)$$

$$C_u = x_{60}/x_{10} \quad (9)$$

$$C_g = x_{30}^2/\left(x_{10} x_{60}\right) \quad (10)$$

$$GS_i = \left(x_{16} + x_{84} - 2x_{50}\right)/2\left(x_{84} - x_{16}\right) + \left(x_5 + x_{95} - 2x_{50}\right)/2\left(x_{95} - x_5\right) \quad (11)$$

$$K_g = \left(x_{95} - x_5\right)/2.44\left(x_{75} - x_{25}\right) \quad (12)$$

$$\sigma_{ig} = \left(x_{84} - x_{16}\right)/4 + \left(x_{95} - x_5\right)/6.6 \quad (13)$$

$$GSD_1 = x_{84}/x_{50} \quad (14)$$

$$GSD_2 = x_{50}/x_{16} \quad (15)$$

$$GSD_{12} = \sqrt{x_{84}/x_{16}} \quad (16)$$

where I_u is the uniformity index, (%); N_{sg} is the size guide number, mm; RS_m is the relative span based on length, dimensionless; C_u is the coefficient of uniformity, dimensionless; C_g is the coefficient of gradation, dimensionless; GS_i is the inclusive graphic skewness, dimensionless; K_g is the graphic kurtosis, dimensionless; n is the Rosin–Rammler distribution parameter, dimensionless; x_R is the parameter or geometric mean of Rosin–Rammler

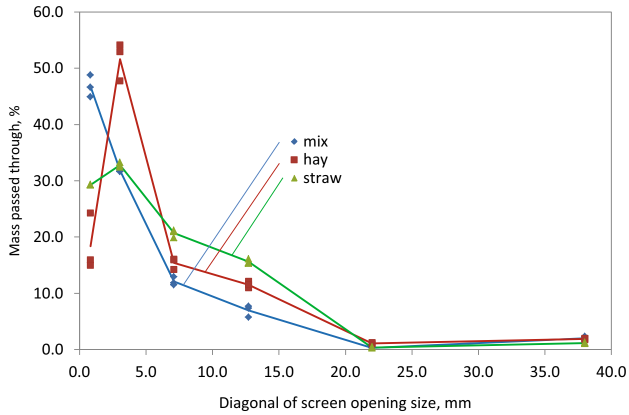

Fig. 1 The shredded biomass particle size distribution

dimension, mm; GSD_1, GSD_2, GSD_{12} are the distribution geometric standard deviation of the high, low and total regions, respectively; and x_{95}, x_{90}, x_{84}, x_{75}, x_{60}, x_{50}, x_{30}, x_{25}, x_{16}, x_{10}, and x_5 are the corresponding particle lengths in mm at respective 95, 90, 84, 75, 60, 50, 30, 25, 16, 10, and 5% cumulative undersizes, which are also known as percentiles.

Statistical analysis was carried out with the use of a standard statistical package Statistica v.12. Statistical inferences were made at the 0.05 level of probability.

Results and Discussion

The particle size density distributions of the biomass are asymmetrical (Fig. 1), with the right-hand skewness. A positive value of graphic kurtosis K_g (Table 1) is a proof of the steepness of distributions. Similar particle distribution trends were observed for hammer mill grinds of wheat, soybean meal, corn [11], alfalfa [18], wheat straw [9, 19], corn stover [6, 9], switchgrass, barley straw [19] and switchgrass [1, 9].

Inclusive graphic skewness GS_i is not very high (0.47–0.67), but the graphic interpretation of density distributions (Fig. 1) allows the inference that there is a very large proportion of finest particles in the mix (hay + straw), and this distribution is similar to the exponential distribution. The other two distributions for hay and straw may be classified as log-normal distributions.

Characteristics of cumulative undersize mass show a rapid achievement of more than 90% of the biomass share with particles less than 8.98 mm, and for a mix with share obtained at a value of $x_{90} = 6.19$ mm (Table 1).

Density distributions of shredded plant material are statistically significantly different between the types of biomass (the value of Fisher–Snedecor test is F = 30.7 with P < 0.0001).

Table 1 The average values of characteristics parameters of shredded biomass

Biomass	x_g (mm)	x_R (mm)	n	x_{10} (mm)	x_{50} (mm)	x_{90} (mm)	RS_m	GS_i	K_g	I_u, %	N_{sg} (mm)	C_u	C_g	σ_{ig} mm	GSD_1	GSD_2	GSD_{12}
Hay	3.45	3.64	0.93	0.32	2.45	8.92	3.51	0.47	1.14	1.67	245	10.23	1.35	3.38	2.84	11.32	5.67
Straw	3.21	3.01	0.85	0.21	1.95	8.05	4.02	0.53	1.20	1.12	195	12.83	1.38	3.09	3.15	14.33	6.72
Mix	2.14	1.73	0.65	0.06	0.99	6.19	6.19	0.67	1.46	0.30	99	27.25	1.52	2.46	4.42	31.44	11.79

x_g, geometric mean of particle size; x_R, geometric mean of Rosin–Rammler dimension; n, Rosin–Rammler distribution parameter; x_{10}, x_{50} and x_{90}, corresponding particle lengths at respective 10, 50 and 90% cumulative undersize; RS_m, relative span based on length; GS_i, inclusive graphic skewness; K_g, graphic kurtosis; I_u, uniformity index; N_{sg}, size guide number; C_u, coefficient of uniformity; C_g, coefficient of gradation; σ_{igs}, inclusive graphic standard deviation; GSD_1, GSD_2, GSD_{12}, distribution geometric standard deviation of the high, low and total regions, respectively

Based on own experience and knowledge from this area and methodology of research, the cumulative mass rate of shredded biomass were approximated by Rosin–Rammler model (RR). For double logarithmic RR model and after receiving a linear function, regression coefficients of equation and its assessments were calculated (Table 2).

In all cases, the evaluation of regression coefficients values are very high, both in relation to the t-Student`s test and P-value, which is not greater than 0.0003. The ratings for regression models are also high; the value of the F—Fisher–Snedecor test exceeds 300, with the critical significance level of $P<0.0001$, and R^2 above 96%.

Curves for the cumulative mass frequency for RR models, against the measuring points shown in Fig. 2, and the characteristic parameters of the particle size distributions are presented in Table 1. The model RR may be used for further analysis and particularly to predicting the separation of material after cutting and grinding meeting the requirements of the particle size for the production of pellets or briquettes.

The graphs (Fig. 2) and the data contained in Table 1 show that 63.2% of the biomass of mix, hay and straw meets the standards of particle size (3.2 mm, according to suggestion by Mani et al. [20]), because the values x_R are 1.73, 3.64 and 3.01 mm, respectively.

The Rosin–Rammler distribution parameters n (slope) were inversely proportional to the kurtosis values (Table 1). This means that a reduced distribution parameter indicated wide distribution. This agrees with published trends [6, 9, 21]. Taking into account the original logarithmic graphical measures classification of Folk and Ward [22] all of these distributions were "very fine skewed" ($0.3 \leq GS_{is} \leq 1.0$) and "leptokurtic" ($1.11 \leq K_{gs} \leq 1.50$). The inclusive standard deviations (σ_{ig}), based on the same classification determine all mixture materials as "very poorly sorted" ($2.0 \leq \sigma_{ig} \leq 4.0$ mm), which indicates that the biomass particle sizes are mixed.

Regarding the value of the geometric mean of particle size x_g of shredded biomass from hay, straw and mix, with dimensions of 3.45, 3.21 and 2.14 mm, respectively, the greatest impact had finest fraction, considered to 10-th percentile of cumulative mass distribution x_{10}, with dimensions of 0.32, 0.21 and 0.06 mm, respectively (Table 1).

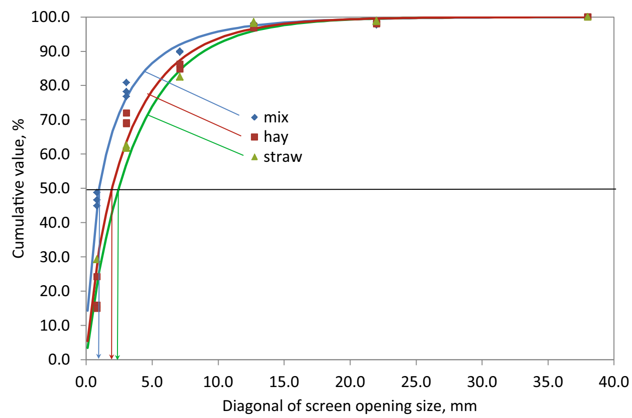

Fig. 2 The cumulative mass frequency of shredded biomass particles

The relatively high share of fine particles in the mixture of shredded material provides greater value of RS_m parameter (Table 1). Shredded material of the mix has a higher share of fine particles, because the average value of the mass share at the span of a sieves set is 6.19. The span was much greater than 1.0, which indicated a 'borderline wide to narrow' distribution (Table 1), and this is opposite to published trends [1, 6], especially for shredded biomass (Table 1). A method of comminute of plant biomass has influence on particle size distribution. The relative span RS_m was inversely proportional to Rosin–Rammler distribution parameter n (Table 1) and this is consistent with Bitra et al. [1, 6].

The smaller mass share on the span of a sieves set, results from the fact of higher values of the distribution uniformity and the uniformity index values I_u (Table 1). The greatest uniformity has mixture of shredded material from hay ($I_u = 1.67\%$) and the lowest – mix ($I_u = 0.30\%$). These parameters are linked to the values of kurtosis and skewness. If the particle size distribution is flatter (less kurtosis value) and symmetric (lower coefficient of skewness value), the mixture is more homogeneous.

Table 2 The values of regression coefficients and their statistical assessments for transformed RR model to linear function $y_t = nx_{Rt}+b$ of cumulative mass rate of shredded biomass

Biomass	Regression coefficient	Rate	Error	t-student	P-value	F-test	P-value for regression	R^2 (%)
Hay	Index *n*	0.93	0.04	20.85	<0.0001	300.9	<0.0001	96.45
	Constant *b*	−0.52	0.05	−10.79	<0.0001			
Straw	Index *n*	0.85	0.03	33.14	<0.0001	868.7	<0.0001	98.56
	Constant *b*	−0.41	0.03	−14.63	<0.0001			
Mix	Index *n*	0.65	0.03	21.12	<0.0001	534.9	<0.0001	96.54
	Constant *b*	−0.16	0.03	−4.61	0.0003			

The size guide number N_{sg} for shredded material is correlated to the value of the dimensionless standard deviation (Table 3), and is 100-times value of it (Table 1).

The value of uniformity coefficient (C_u) for shredded material from hay is the smallest (10.23) and the highest is for mix (27.25), which confirms the irregularity of the particle size of that biomass. Material uniformity coefficient of <4.0 is likely to contain particles having a relatively aligned size [23]. Coefficient of uniformity above 4.0 is obtained with a larger range of particles size distribution dispersion. For this reason, all particle size distributions of shredded material must be regarded as almost uniform, which is typical for the fiber [24] and long twisted materials that are bent during transport in the shredding machine, and at the time of their separation under external load.

Coefficient of gradation for particle size distribution (C_g) is in a narrow range and is from 1.35 for hay to 1.53 for mix (Table 1). Coefficient of gradation in the range of 1–3 represents a well-graded particle size distribution [23]. It can therefore be concluded that the tested biomass material has relatively good grading particle size distribution.

Distribution geometric standard deviation of the high GSD_1, low GSD_2 and total GSD_{12} regions (Table 1) are negatively correlated with the values of the geometric mean of particle size x_g (Table 3). Less dispersion of the particle size is in the upper zone of the distribution than in the lower one, because values for biomass material are in the range 2.84–4.42. Distribution geometric standard deviation of the total region of the shredded material is the lowest for hay (5.67), and the largest for mix (11.79). These values correlated strongly positively with the coefficients of uniformity C_u and gradation C_g of particle size distribution (Table 1).

The results of variance analysis of geometric mean of particle size x_g from shredded plant biomass, dimensionless standard deviation s_g and dimensional one s_{gw} are summarized in Tables 3 and 4.

In all cases, the calculated parameters of the particle size distributions are significantly different for the type of material. Geometric mean of particle size for whole mixtures are statistically significantly different between each biomass, creating separate homogeneous groups (Table 3) and the values for mix, hay and straw are 2.14, 2.96 and 3.20 mm, respectively. The standard deviations s_g of the dimensionless particle size are practically poorly varied for biomass types (Table 3) and the dimensional standard

Table 3 The values of geometric mean of particles size of shredded plant biomass x_g, dimensionless standard deviation s_g and dimensional s_{gw} and their standard deviations SD and 95% confidence intervals with their statistical analysis by Duncan test

Biomass	x_g (mm)	SD x_g (mm)	−95% x_g (mm)	+95% x_g (mm)
Hay	2.96^{b*}	0.04	2.87	3.05
Straw	3.20^{c}	0.04	3.11	3.30
Mix	2.14^{a}	0.04	2.04	2.23
Biomass	s_g	SD s_g	−95% s_g	+95% s_g
Hay	2.61^{a}	0.02	2.56	2.66
Straw	2.79^{b}	0.02	2.74	2.84
Mix	2.78^{b}	0.02	2.73	2.83
Biomass	s_{gw} (mm)	SD s_{gw} (mm)	−95% s_{gw} (mm)	+95% s_{gw} (mm)
Hay	20.01^{b}	0.56	18.74	21.27
Straw	26.04^{c}	0.56	24.78	27.31
Mix	17.23^{a}	0.56	15.97	18.50

*Means with same letters are not significant different at P <0.05 using Duncan test

Table 4 The variance analysis results of geometric mean of particles size of shredded plant biomass x_g, dimensionless s_g and dimensional standard deviation s_{gw}

Parameter	Source	Sum of squares	Degrees of freedom	Mean square	F-test	P-value
x_g	Shredded material	2.497	2	1.248	179.7	<0.0001
	Error	0.063	9	0.007		
s_g	Shredded material	0.083	2	0.042	23.3	0.0003
	Error	0.016	9	0.002		
s_{gw}	Shredded material	162.3	2	81.2	65.1	<0.0001
	Error	11.2	9	1.2		

deviations are consequence of the previous parameters, particularly geometric mean, therefore, that large spread of s_{gw} values from 17.23 to 26.04 mm (Table 3) for a full sample of biomass. Bitra et al. [9] found that average geometric standard deviation (dimensionless) increased slightly from 2.5 ± 0.1 to 2.7 ± 0.1 with an increase in screen size from 12.7 to 25.4 mm and decreased to 2.6 ± 0.1 for further increase to 50.8 mm, but these figures show that the differences were not large. Geometric standard deviation (dimensionless) is therefore not a relevant evaluation criterion parameter and should be found an another indicator. All of these parameters describe the shredded biomass and depend on the material properties, conditions of agglomeration process and storage. Moreover, the particle sizes are important parameters which determine the susceptibility of biomass concentration, particle packing, moving between adjacent particles, the ability to link and create a permanent mechanical or chemical bonds and, therefore, affect the stability of the produced pellets. That requires further extended studies, taking into account mix of hay and straw as preferable material for making pellets according to its better fragmentation. However it is less homogenous as a result of high share of fine particles at dimension under 1.65 mm. The particle size distribution of finest particles should be verified, taking into account that small and medium-sized particles are desired in the granulation process [25]. Smaller particles influence the growth of the efficiency process and reduce pelleting costs. Very small particles however, may cause disturbances in the granulation process due to clogging of granulators dies.

Conclusions

1. Regarding the value of the geometric mean of particle size x_g of shredded biomass from hay, straw and mix, with dimensions of 3.45, 3.21 and 2.14 mm, respectively, the greatest impact had finest fraction, considered to 10-th percentile of cumulative mass distribution x_{10}, with dimensions of 0.32, 0.21 and 0.06 mm, respectively.
2. The indicators used to evaluate the size distributions are good measures, especially in relation to evaluate the contribution of the finest particles. For hay, straw and mix the mass relative span RS_m of fine fraction was 3.51, 4.02 and 6.19, respectively. It was reverse of distribution uniformity index (I_u rate was 1.67, 1.12 and 0.30%, respectively), confirmed by lower values of kurtosis K_g 1.14, 1.20 and 1.46, respectively, and inclusive graphic skewness GS_i 0.47, 0.53 and 0.67, respectively, and the coefficient of uniformity C_u 10.23, 12.83 and 27.25 respectively. That correlated positively with the coefficient of gradation C_g and the distribution geometric standard deviation of the high GSD_1, low GSD_2 and total GSD_{12} regions (Table 1).

Compliance with Ethical Standards

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

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