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The characteristics of shredded straw and hay and their mix

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Abstract: *The characteristics of shredded straw and hay and their mix*. The aim of this study was to determine the characteristics of shredded biomass from hay, straw and their mix in the ratio of 1 : 1 using a sieve separator. The research was carried out according to method described in ANSI/ASAE S319.4 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: 0.65, 0.63 and 0.92 mm, respectively, the greatest impact had the smallest fraction, considered to 25th percentile of cumulative mass distribution x_{25}, with dimensions of 0.41, 0.28 and 0.47 mm, respectively. The particles of hay were more uniform and belong to "well sorted" category than particles of straw and mix, which were non-uniform and belong to "moderately well sorted" category. All biomass particles size distribution were "positively skewed" and "leptokurtic". On dimensional standard deviation (s_{gw}) the dimensionless standard deviation (s_g) had a greater impact than the particle size (x_g).

Key words: biomass, distribution, particle size, RR model

INTRODUCTION

Shredding process changes the particle size distribution, particle size and shape, increases bulk density, improves flow properties, increases porosity, and generates new surface area [Bitra et al. 2009b, Nowakowski and Ślesiński 2012, Nowakowski 2015]. Mani et al. [2006] report that the particle size has influence on the mechanical properties of the pellets of straw from wheat, barley and corn.

Assessment of particle size and size distribution of shredded biomass, an essential first stage of measurement, can be obtained by utilizing several methods such as the basic mechanical sieving [Bitra et al. 2009c, Igathinathane et al. 2009b, ASABE Standard 2011a], and advanced light scattering, acoustic spectroscopy, and laser diffraction methods. These advanced instruments are highly expensive and often assume a spherical geometry for the irregular sample particles in the analysis.

Results from particle size distribution analysis include percentage of particles remained 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 [Blott and Pye 2001, Igathinathane et al. 2009b].

Finding acceptable mathematical functions to describe particle size distribution data may extend the application of empirical data [Bitra et al. 2009b]. Rosin and Rammler [1933] stated their equation as a universal law of size distribution valid for all powders, irrespective of the nature of material and the method of grinding. Among at least three common size distribution functions (log-normal, Rosin–Rammler and Gaudin–Schuhmann) tested on different fertilizers, the

Rosin-Rammler function was the best function based on an analysis of variance [Perfect and Xu 1998, Allaire and Parent 2003].

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

MATERIAL AND METHODS

The shredded material from straw, hay and mix at a mass ratio of 1:1 had a moisture 5.70 ±0.48, 6.00 ±0.21 and 6.33 ±0.35%, respectively.

Plant material moisture content was carried out by drying-weighting method according to the ASAE S358.2 standard [ASABE Standards 2011b].

Using sieve separator (set of sieves from the below: span, dimensions of opening screens in the sequence: 0.045, 0.056, 0.1, 0.15, 0.212, 0.3, 0.425, 0.6, 0.85, 1.18, 1.6 and 2.36 mm) with vibratory motion in vertical plane, shredded biomass were separated according to the standard of ANSI/ASAE S319.4 [ASABE Standards 2011a]. Each sample was sieved five times.

For the purpose of the distribution geometric mean of particle size (x_g), dimensionless standard deviation (s_g) and dimensional standard deviation (s_{gw}) were determined from the following relations:

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

$$s_g = \log^{-1}\sqrt{\sum\left[m_i\left(\log x_{si} - \log x_g\right)^2\right]/\sum m_i}$$

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

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

$$x_{si} = \sqrt{x_i x_{i-1}}$$

where:
x_i – holes diagonal of i-th sieve [mm];
$x_{(i-1)}$ – 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 [Rosin and Rammler 1933] in the following form:

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

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

Dimensions of significance based on length and their distribution were derived from the cumulative undersize characteristics of particle dimensions original data. The following several common particle size distribution parameters based on length were evaluated from these significant dimensions [Blott and Pye 2001, Allaire and Parent 2003, Craig 2004, Allais et al. 2006, Bitra et al. 2009c, Igathinathane et al. 2009a, b].

$$I_u = 100\frac{x_5}{x_{90}}$$

$$N_{sg} = 100x_{50}$$

$$S_v = 100(x_{84} - x_{16})/2x_{50}$$

$$S_l = (x_{90} - x_{10})/x_{50}$$

$$C_u = x_{60}/x_{10}$$

$$C_g = x_{30}^2/(x_{10}x_{60})$$

$$x_{gm} = (x_{16} + x_{50} + x_{84})/3$$

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

$$S_{ig} = (x_{16} + x_{84} - 2x_{50})/2(x_{84} - x_{16}) + \\ + (x_5 + x_{95} - 2x_{50})/2(x_{95} - x_5)$$

$$K_g = (x_{95} - x_5)/2.44(x_{75} - x_{25})$$

$$STD_h = x_{84}/x_{50}$$

$$STD_l = x_{50}/x_{16}$$

$$STD_t = \sqrt{x_{84}/x_{16}}$$

where:
I_u – uniformity index [%];
N_{sg} – size guide number [mm];
S_v – size range variation [%];
S_l – relative span based on length [–];
C_u – coefficient of uniformity [–];
C_g – coefficient of gradation [–];
x_{gm} – graphic mean [mm];
σ_{ig} – inclusive graphic standard deviation [mm];
S_{ig} – inclusive graphic skewness [–];
K_g – graphic kurtosis [–];
n – Rosin–Rammler distribution parameter [–];
x_R – parameter of geometric mean of Rosin–Rammler dimension [mm];
STD_h, STD_l, STD_t – distribution geometric standard deviation of the high, low and total regions, respectively;
x_{95}, x_{90}, x_{84}, x_{75}, x_{60}, x_{50}, x_{30}, x_{25}, x_{16}, x_{10}, x_5 – corresponding particle lengths [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. Hay was characterized by a higher share of fine particles than straw and mix, which the characteristics up to 1.00 mm size were similar. At mix was found a significant share of the biggest particles above 2.81 mm. 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

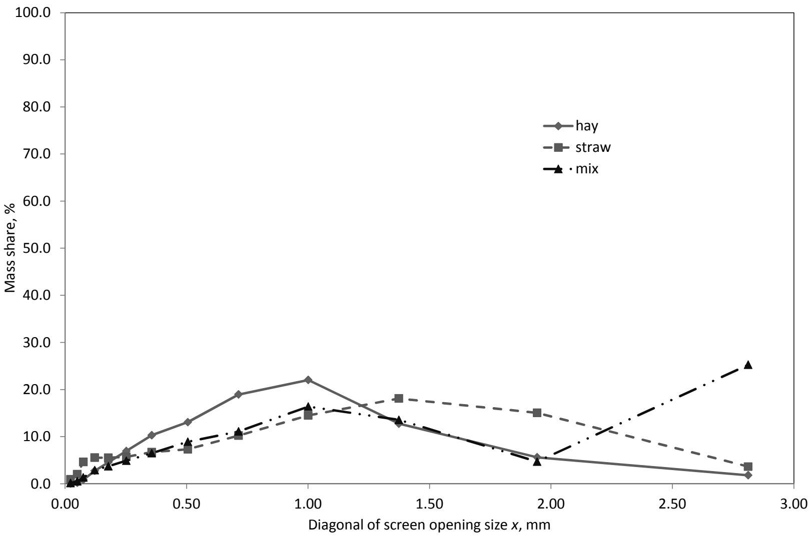

FIGURE 1. The shredded plant biomass size distribution from sieve separator

TABLE 1. The average values of characteristics parameters of shredded biomass

Parameter	Hay	Straw	Mix
x_g [mm]	0.65[a*]	0.63[a]	0.92[b]
s_g	2.09[a]	2.95[c]	2.60[b]
s_{gw} [mm]	40.15[a]	280.39[c]	185.11[b]
x_R [mm]	0.78	0.75	1.01
b	0.212	0.155	–0.004
n	1.962	1.255	1.609
x_5 [mm]	0.17	0.07	0.16
x_{10} [mm]	0.25	0.12	0.25
x_{16} [mm]	0.32	0.19	0.34
x_{25} [mm]	0.41	0.28	0.47
x_{30} [mm]	0.46	0.33	0.53
x_{50} [mm]	0.65	0.56	0.80
x_{60} [mm]	0.75	0.7	0.96
x_{75} [mm]	0.92	0.97	1.24
x_{84} [mm]	1.06	1.22	1.47
x_{90} [mm]	1.19	1.46	1.70
x_{95} [mm]	1.36	1.80	2.00
I_u [%]	14.29	4.79	9.41
N_{sg} [mm]	65	56	80
S_v [%]	56.92	91.96	70.63
S_l	1.45	2.39	1.81
C_u	3.00	5.83	3.84
C_g	1.13	1.30	1.17
x_{gm} [mm]	0.68	0.66	0.87
σ_{ig} [mm]	0.37	0.52	0.56
S_{ig}	0.15	0.36	0.25
K_g	0.96	1.03	0.98
STD_h [mm]	1.63	2.18	1.84
STD_l [mm]	2.03	2.95	2.35
STD_t [mm]	1.82	2.53	2.08

x_g – geometric mean of particle size; s_g – standard deviation of geometric mean of particle size, x_R – geometric mean of Rosin–Rammler dimension; b – constant at leaner Rosin–Rammler regression; n – Rosin–Rammler distribution parameter; x_{95}, x_{90}, x_{84}, x_{75}, x_{60}, x_{50}, x_{30}, x_{25}, x_{16} and x_{10} – corresponding particle lengths at respective 95, 90, 84, 75, 60, 50, 30, 25, 16, 10, and 5% cumulative undersize; I_u – uniformity index; N_{sg} – size guide number; S_l – relative span; C_u – coefficient of uniformity; C_g – coefficient of gradation; x_{gm} – graphic mean; σ_{ig} – inclusive graphic standard deviation; S_{ig} – inclusive graphic skewness; K_g – graphic kurtosis; STD_h, STD_l, STD_t – distribution geometric standard deviation of the high, low and total regions, respectively.
[*] Means with the same letters are not significant different at p <0.05 using Duncan test.

meal, corn [Pfost and Headley 1976], alfalfa [Yang et al. 1996], wheat straw [Mani et al. 2004, Bitra et al. 2009a], corn stover [Bitra et al. 2009a, c, Lisowski et al. 2014b], switchgrass, barley straw [Mani et al. 2004], switchgrass [Bitra et al. 2009a, b] and giant miscanthus, giant knotweed, Virginia mallow, *Spartina pectinata*, Jerusalem artichokes, big bluestem, switchgrass [Lisowski et al. 2014a].

Based on own experience and knowledge from this area and method 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).

and the characteristic parameters of the particle size distributions are presented in Table 1. The model RR may will 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 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 [Jaya and Durance 2007, Bitra 2009a, c].

Figure 2 and the data contained in Table 1 show that 95% of the biomass of hay, straw and mix meets the standards of particle size (3.2 mm, according

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	Coefficient	Rate	Error	t-Student	p	F	p	R^2 [%]
Hay	index n	0.212	0.027	7.87	<0.0001	3 293	<0.0001	98.12
	constant b	1.962	0.034	57.39	<0.0001			
Straw	index n	0.155	0.021	7.50	<0.0001	2 281	<0.0001	97.31
	constant b	1.255	0.026	47.76	<0.0001			
Mix	index n	–0.004	0.030	–0.12	<0.0001	1 724	<0.0001	96.48
	constant b	1.609	0.039	41.53	0.0003			

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 0.0001. The ratings for regression models are also high; the value of the F – Fisher–Snedecor test exceeds 1,724, with the critical significance level of p <0.0001, and $R^2 > 96\%$.

Curves for the cumulative mass frequency for RR models, against the measuring points are shown in Figure 2, to suggestion by Mani et al. [2003], because the values x_{95} are 1.36, 1.80 and 2.00 mm, respectively).

Regarding the value of the geometric mean of particle size (x_g) of shredded biomass from hay, straw and mix, with dimensions of 0.65, 0.63 and 0.92 mm, respectively, the greatest impact had finest fraction, considered to 25th percentile of cumulative mass distribution x_{25}, with dimensions of 0.41, 0.28 and 0.47 mm, respectively (Table 1).

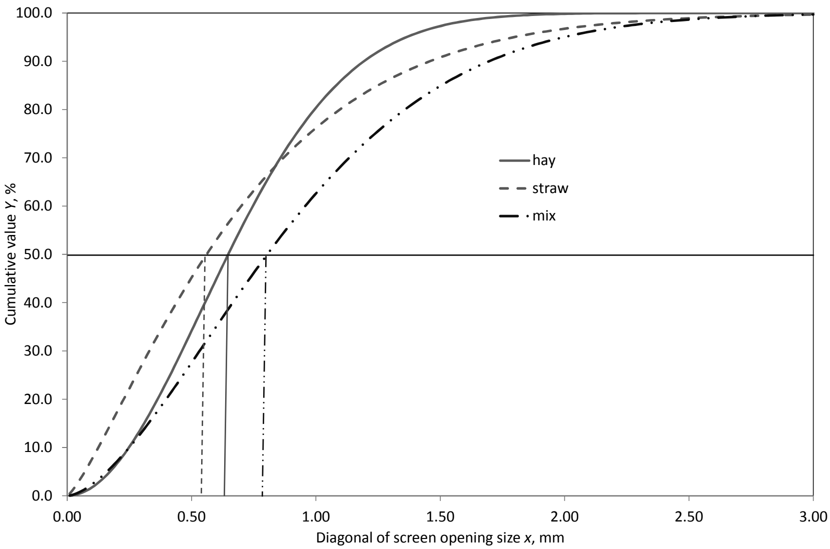

FIGURE 2. The RR model for cumulative mass frequency of plant biomass, against the measuring points from sieve separator with vibratory motion in vertical plane

The relatively high share of fine particles in the mixture of shredded material provides greater value of S_l parameter (Table 1). Shredded material of the straw has a higher share of fine particles, because the average value of the mass share at the span of a sieves set is 2.39. The relative span (S_l) was inversely proportional to Rosin–Rammler distribution parameter – n (Table 1) and this is consistent with Bitra et al. [2009b, c].

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 = 14.29%) and the lowest – straw (I_u = 4.79%). 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.

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

The value of uniformity coefficient (C_u) for shredded material from hay is the smallest (3.00) and the highest is for a straw (5.83), which confirms the irregularity of the particle size of that biomass. Material uniformity coefficient of below 4.0 is likely to contain particles having a relatively aligned size [Budhu 2007].

Coefficient of gradation for particle size distribution (C_g) is in a narrow range and is from 1.13 for hay to 1.30 for straw (Table 1). Coefficient of gradation in the range of 1–3 represents a well-graded particle size distribution [Budhu 2007].

The inclusive graphic standard deviations (σ_{ig}) descriptively classify the particulate material based on Folk and Ward [1957] logarithmic original graphical measures classification [Blott and Pye 2001]. The classification obtained from determined values (Table 1) were: hay as "well sorted" ($0.35 \leq \sigma_{ig} \leq 0.50$); straw and mix as "moderately well sorted ($0.50 \leq \leq \sigma_{ig} \leq 0.70$). It should be noted these classifications are subjected to change when the same material of the sample were processed under different processing machine settings, such as clearance and product classification screen opening dimensions.

On the basis of correlation of the particle size parameters x_g, s_g and s_{gw} non--linear models were developed, and the values of regression coefficients and their evaluation are listed in Table 3. Regression coefficient values are statistically significant, and the evaluation value for the regression is greater than 99.86%.

For straw dimensional standard deviation (s_{gw}) to the greatest extent it depends on the particle size (x_g) and dimensionless standard deviation (s_g), and the least for hay. On dimensional standard deviation (s_{gw}) the dimensionless standard deviation (s_g) had a greater impact than the particle size (x_g).

CONCLUSIONS

1. Regarding to the value of the geometric mean of particle size x_g of shredded biomass from hay, straw and mix, with dimensions of 0.65, 0.63 and 0.92 mm, respectively, the greatest impact had the finest fraction, considered to 25th percentile of cumulative mass distribution x_{25}, with dimensions of 0.41, 0.28 and 0.47 mm, respectively.
2. The particles of hay were more uniform and belonged to "well sorted" category than particles of straw and mix, which were non-uniform and belonged to "moderately well sorted" category. All biomass particles size distribution were "positively skewed" and "leptokurtic".
3. On dimensional standard deviation (s_{gw}) the dimensionless standard deviation (s_g) had a greater impact than the particle size (x_g).

TABLE 3. The values of regression coefficients and their statistical assessments for non-linear model involves dimensional standard deviation (s_{gw}) with geometric mean of particles size of shredded plant biomass (x_g) and dimensionless standard deviation (s_g)

Biomass	Coefficient	Rate	Error	t-Student	p	F	p	R^2 [%]
Hay	constant	–194.23	3.29	–59.02	0.0003	4 490	0.0002	99.98
	x_g	67.56	5.85	11.55	0.0074			
	s_g	91.07	1.23	73.84	0.0002			
Straw	constant	–2 151.50	177.14	–12.15	0.0067	717	0.0014	99.86
	x_g	545.36	93.02	5.86	0.0279			
	s_g	708.75	40.95	17.31	0.0033			
Mix	constant	–1 108.57	59.39	–18.67	0.0029	1 503	0.0007	99.93
	x_g	204.94	20.67	9.91	0.0100			
	s_g	424.41	15.76	26.93	0.0014			

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Streszczenie: *Charakterystyki rozdrobnionej słomy, siana i ich mieszanki.* Celem badań jest opracowanie charakterystyk rozdrobnionej biomasy z siana, ze słomy i z ich mieszanki, w 1 : 1, na podstawie analizy sitowej. Badania przeprowadzono zgodnie z metodą opisaną w normie ANSI/ASAE S319.4. Wartość średniej geometrycznej wymiarów cząstek x_g rozdrobnionej biomasy z siana, ze słomy i z ich mieszanki wynosiła odpowiednio 0,65, 0,63 i 0,92 mm, a największy wpływ na tę średnią miał udział 25. percentyla skumulowanego rozkładu masy x_{25} o wymiarach, odpowiednio 0,41, 0,28 i 0,47 mm. Cząstki siana były bardziej jednolite i należały do kategorii „dobrze sortowane" niż cząstki słomy i mieszanki, które były niejednorodne i należały do kategorii „umiarkowanie dobrze sortowane". Rozkłady wymiarów cząstek wszystkich próbek charakteryzowały się prawostronną skośnością i były leptokurtyczne (nieznacznie strome). Na odchylenie standardowe wymiarowe s_{gw} większy wpływ miało odchylenie standardowe bezwymiarowe s_g niż wartość średniej wymiarów cząstek x_g.

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