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Knife mill operating factors effect on switchgrass particle size distributions

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ABSTRACT

Biomass particle size impacts handling, storage, conversion, and dust control systems. Switchgrass (*Panicum virgatum* L.) particle size distributions created by a knife mill were determined for integral classifying screen sizes from 12.7 to 50.8 mm, operating speeds from 250 to 500 rpm, and mass input rates from 2 to 11 kg/min. Particle distributions were classified with standardized sieves for forage analysis that included horizontal sieving motion with machined-aluminum sieves of thickness proportional to sieve opening dimensions. Then, a wide range of analytical descriptors were examined to mathematically represent the range of particle sizes in the distributions. Correlation coefficient of geometric mean length with knife mill screen size, feed rate, and speed were 0.872, 0.349, and 0.037, respectively. Hence, knife mill screen size largely determined particle size of switchgrass chop. Feed rate had an unexpected influence on particle size, though to a lesser degree than screen size. The Rosin–Rammler function fit the chopped switchgrass size distribution data with an $R^2 > 0.982$. Mass relative span was greater than 1, which indicated a wide distribution of particle sizes. Uniformity coefficient was more than 4.0, which indicated a large assortment of particles and also represented a well-graded particle size distribution. Knife mill chopping of switchgrass produced 'strongly fine skewed mesokurtic' particles with 12.7–25.4 mm screens and 'fine skewed mesokurtic' particles with 50.8 mm screen. Results of this extensive analysis of particle sizes can be applied to selection of knife mill operating parameters to produce a particular size of switchgrass chop, and will serve as a guide for relations among the various analytic descriptors of biomass particle distributions.

1. Introduction

Bio-based power, fuels, and products may contribute to worldwide energy supplies and economic development. Switchgrass is widely recognized as a leading crop for energy production (Greene, 2004). For efficient conversion of biomass to bioenergy, an optimized supply chain ensures timely supply of biomass with minimum costs (Kumar and Sokhansanj, 2007). Size reduction is an important energy intensive unit operation essential for bioenergy conversion process and densification to reduce transportation costs. Biomass size reduction process changes the particle size and shape, increases bulk density, improves flow-properties, increases porosity, and generates new surface area (Drzymala, 1993). However, physical- and flow-properties of biological materials are highly dependent on particle size and distribution (Ortega-Rivas, 2003). Fine corn flour particle size was found to improve hydrolysis yields (Naidu and Singh, 2003). Corn stover particle size reduction and separation to various size fractions affected pretreatment and hydrolysis processes (Chundawat et al., 2006). Higher surface area increases number of contact points for chemical reactions (Schell and Harwood, 1994), which may require grinding to a nominal particle size of about 1 mm (US Department of Energy, 1993). Size reduction alone can account for one-third of the power requirements of the entire bioconversion to ethanol (US Department of Energy, 1993). Particle size analyses characterize the input and output materials of size reduction operations that usually produce a range of particle sizes or distribution, within a given sample.

Current research is driven by the need to reduce the cost of biomass ethanol production. Pretreatment research is focused on developing processes that would result in reduced bioconversion time, reduced enzyme usage and/or increased ethanol yields (Silverstein et al., 2007). Efficient size reduction emphasizes delivery of suitable particle size distributions, though information to predict particle size distributions is lacking for most of the newly considered biomass sources such as switchgrass.

Nominal biomass particle sizes produced by knife mill chopping depend on screen size of the mill. Himmel et al. (1985) observed chopped wheat straw retention of 30–85% on 20–60 mesh size

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for knife mill screens ranging from 12.7 to 1.6 mm, respectively. They found that 50% of chopped aspen was retained at 6–14 mesh for 12.7–3.2 mm knife mill screens, respectively.

Particle size distribution of hammer-milled alfalfa forage grinds were fitted with a log-normal distribution equation (Yang et al., 1996). They found that median size and standard deviation were 238 and 166 μm, respectively. Mani et al. (2004a) determined sieve-based particle size distribution of wheat and barley straws, corn stover, and switchgrass and established relationships for bulk density with geometric mean particle size. Particle size distribution of corn stover grind from different hammer mill screens depicted positive skewness in distribution (Mani et al., 2004b). In actual practice, measured geometric mean length of biomass particles using sieve analysis is less than the actual size of the particles (Womac et al., 2007). They reported that geometric mean dimensions of actual biomass particles varied from 5× for particle length to 0.3× for particle width for knife milled switchgrass, wheat straw, and corn stover when compared to geometric mean length computed from American Society of Agricultural and Biological Engineers (ASABE) sieve results. Geometric mean dimensions of switchgrass were accurately measured using an image analysis technique as verified with micrometer measurements (Yang et al., 2006). However, sieves have a long history and acceptance in various industries and provide a standardized format for measuring particle sizes, even with published values of offset.

Finding acceptable mathematical functions to describe particle size distribution data may extend the application of empirical data. 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 (Allaire and Parent, 2003; Perfect and Xu, 1998). Also, particle size distributions of alginate–pectin microspheres were well-fit with the Rosin–Rammler model (Jaya and Durance, 2007).

Little published data provide information on knife mill particle size distribution of switchgrass due to various knife mill operating factors. Hence, the objective of this research was to evaluate Rosin–Rammler particle size distribution mathematical function and other analytic descriptors of particle distributions for standardized forage sieve results obtained for chopped switchgrass prepared with a knife mill operated at various mill operating factors.

2. Methods

2.1. Biomass test material

Switchgrass (*Panicum virgatum* L.; *Cultivar*. Alamo) had been harvested as hay and allowed to dry in a swath prior to baling and then bales were stored indoors for three months. Switchgrass bales (1.00 × 0.45 × 0.35 m) were manually de-stringed for sample mass determinations. Moisture content of switchgrass was 9.0 ± 0.5% wet basis measured using ASABE Standard S358.2 for forages (ASABE Standards, 2006a) by oven drying the samples at 103 ± 2 °C for 24 h.

2.2. Knife mill and operating variables

A commercially-available knife mill (H.C. Davis Sons Mfg. Co., Inc., Bonner Springs, KS) with a 400 mm diameter rotor powered with a gasoline engine rated at 18 kW was used for switchgrass chopping. The knife mill rotor had eight 75 mm-wide straight knife blades bolted to its periphery. Length and thickness of single bevel edge blade were 600 and 12 mm, respectively. Knife blade tip angle was 45°. Blades cleared two stationary shear bars indexed at about 10 o'clock and 2 o'clock angular positions. A uniform blade clearance of 3 mm was used. Knife mill was equipped with an interchangeable classifying screen that was mounted in an arc on the bottom side of rotor. Screens enclosed about 240° of sector angle around the rotor. Screen selections tested had opening diameters ranging from 12.7 to 50.8 mm. Engine rated speed of 3600 rpm using a V-belt drive system gave knife mill speed of 507 rpm. Various engine throttle settings operated the knife mill at speeds ranging from 250 to 500 rpm to examine speed effects. In addition to continuous monitoring with a speed sensor (Series 4200 PCB Piezotronics, Depew, NY, USA), independent measures of knife mill speeds were taken with a handheld laser photo tachometer (±0.05% accuracy).

2.3. Mass feed control to knife mill and sample collection

Weighed switchgrass samples (±50 g accuracy) were evenly distributed on a 6.1 m long inclined belt conveyor (Automated Conveyor Systems, Inc., West Memphis, Arkansas, USA). Belt speed was adjusted to feed the switchgrass in 1 min. This arrangement provided a means to uniformly feed switchgrass sample into knife mill at a measured rate. Sample feed rates ranged from 2 to 11 kg/min. Maximum mass feed rates were determined in pre-tests and were usually controlled by knife mill screen opening size and rotor speed. Chopped switchgrass passed down through knife mill screen at bottom and was collected below the screen. Collected sample was mixed thoroughly and a representative sample of about 1 kg was bagged in polyethylene bags for analysis of particle size distribution using ASABE sieve analyzer.

2.4. Sieve analysis

Each switchgrass sample after size reduction was subjected to particle size distribution analysis following ASABE standard S424.1 (ASABE Standards, 2006b). A sieve analyzer (Fig. 1) was constructed with two stacks of sieves to balance weight of complex elliptical motion of masses. First stack contained two sieves (19.0 and 12.7 mm nominal opening size) and a pan. The counter balancing second stack contained three sieves (6.30, 3.96, and 1.17 mm nominal opening size) and a pan. Diagonal sieve opening sizes were 26.90, 18.00, 8.98, 5.61, and 1.65 mm. After the particles had been sieved by first stack, particles in first pan were transferred to second stack of sieves for remaining separation pass while the first stack was engaged for next sample. Particles from each sieve were collected and weighed using an electronic top pan balance (±0.01 g accuracy). The sieve was operated for 10 min (Yang, 2007).

2.5. Data analysis

Log-normal distribution plots of switchgrass between percent retained mass and geometric mean length of particles on each sieve, $\overline{X_i}$, were graphed with semi-log scale. Geometric mean length and geometric standard deviation were calculated based on mass fraction using the following equations (ASABE Standards, 2006b):

$$X_{gm} = \ln^{-1}\left[\frac{\Sigma(M_i \ln \overline{X_i})}{\Sigma M_i}\right] \quad (1)$$

$$S_{gm} = \ln^{-1}\left[\frac{\Sigma(M_i(\ln \overline{X_i} - \ln X_{gm})^2)}{\Sigma M_i}\right]^{1/2} \quad (2)$$

where, X_{gm} is geometric mean length, mm; S_{gm} is geometric standard deviation (dimensionless) (Hinds, 1982); X_i is diagonal of sieve

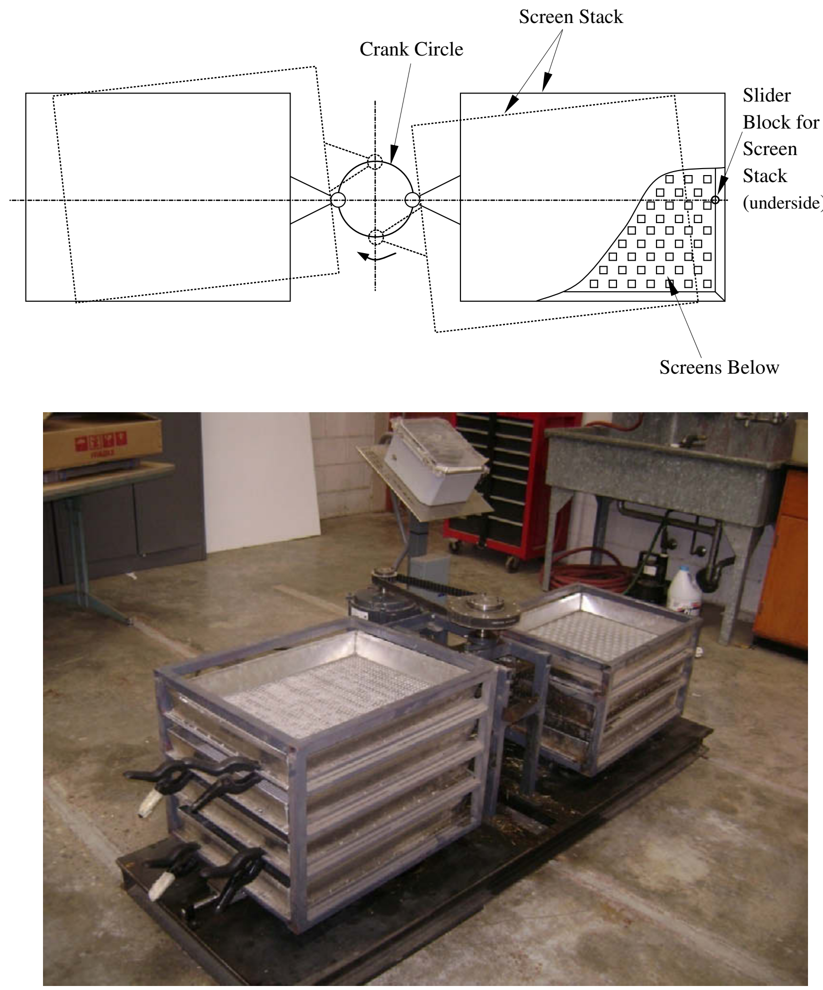

Fig. 1. Overhead view and photo of sieve analyzer.

openings of ith sieve, mm; $X_{(i-1)}$ is diagonal of sieve openings in next larger than ith sieve, mm; $\overline{X_i}$ is geometric mean length of particles on ith sieve or $[X_i \times X_{(i-1)}]^{1/2}$, mm; and, M_i is mass on ith sieve, g (ASABE Standards, 2006b).

Percent cumulative undersize mass of switchgrass particles, as a function of diagonal sieve opening size, were graphed on semi-log plots. Curves were characterized as well-graded, gap (step)-graded, or poorly-graded. 'Well-graded' means no excess of particles in any size range and no intermediate sizes are lacking. A gradual rising trend in the cumulative curve represents well-graded particles. Particles said to be 'poorly-graded' if a high proportion of particles have sizes within narrow limits (uniform particles). If particles of both large and small sizes are present, but have a relatively low proportion of particles of intermediate size, then they are assigned as gap- or step-graded particles (Budhu, 2007; Craig, 2004). A steep cumulative curve represents poorly-graded particles, whereas a flattened curve represents gap- or step-graded particles. Cumulative undersize mass percentage data obtained through ASABE sieve analysis was regressed using Rosin–Rammler distribution equation (Rosin and Rammler, 1933). This equation was selected based on previous success with sieved materials (Allaire and Parent, 2003; Djamarani and Clark, 1997; Jaya and Durance, 2007; Perfect and Xu, 1998). Rosin–Rammler equation is as follows:

$$M_{cu} = 100\left[1 - e^{-\left(\frac{D_p}{a}\right)^b}\right] \tag{3}$$

where, M_{cu} is cumulative undersize mass, %; D_p is particle size, assumed equivalent to diagonal sieve opening, mm; a is size parameter, or Rosin–Rammler geometric mean length, mm; and, b is distribution parameter, or Rosin–Rammler skewness parameter (dimensionless). Particle size at any percentile of cumulative undersize mass was calculated by rearranging Eq. (3) as follows:

$$D_p = a\left[-\ln\left(1 - \frac{M_{cu}}{100}\right)\right]^{1/b} \tag{4}$$

From Eq. (4), particle sizes in mm corresponding to 10%, 50%, and 90% cumulative undersize mass (D_{10}, D_{50} (median length), and D_{90}, respectively) were evaluated to calculate mass relative span as an indicator of distribution width. It should be noted that median length is different from geometric mean length for skewed distribution (Hinds, 1982). The size D_{10} is also known as effective size (Craig, 2004). Mass relative span, RS_m, provides a dimensionless measure of particle size distribution width (Allais et al., 2006) and was determined as follows:

$$RS_m = (D_{90} - D_{10})/D_{50} \tag{5}$$

where D_{10}, D_{50}, and D_{90} are particle lengths in mm at 10th, 50th, and 90th percentiles of cumulative mass distribution, respectively.

Another difference among particle size distributions may be skewness. Skewness measures degree of asymmetry of normal distribution curve and its sign denotes whether a curve has an asymmetrical tail on its left or right when distribution is plotted versus particle size. Inclusive graphic skewness of particle size distribution (Folk, 1974), which includes 90% of the curve, was calculated from the following equation:

$$GS_i = (D_{16} + D_{84} - 2D_{50})/(2(D_{84} - D_{16})) + (D_5 + D_{95} - 2D_{50})/(2(D_{95} - D_5)) \quad (6)$$

where, GS_i is inclusive graphic skewness; and D_5, D_{16}, D_{84}, and D_{95} are particle sizes in mm corresponding to 5%, 16%, 84%, and 95% cumulative undersize mass, respectively. Interval between D_5 and D_{95} points on normal probability curve should be exactly 2.44 times the interval between D_{25} and D_{75} points. Departure from this ratio or normality is represented by kurtosis or peakedness. It measures the sorting in the tails of distribution curve and the sorting in central portion. Graphic kurtosis of particle size distribution (Folk, 1974), which includes 90% of the curve, was measured using equation:

$$K_g = (D_{95} - D_5)/(2.44(D_{75} - D_{25})) \quad (7)$$

where, K_g is graphic kurtosis; and D_{25}, and D_{75} are particle sizes in mm corresponding to 25% and 75% cumulative undersize mass, respectively.

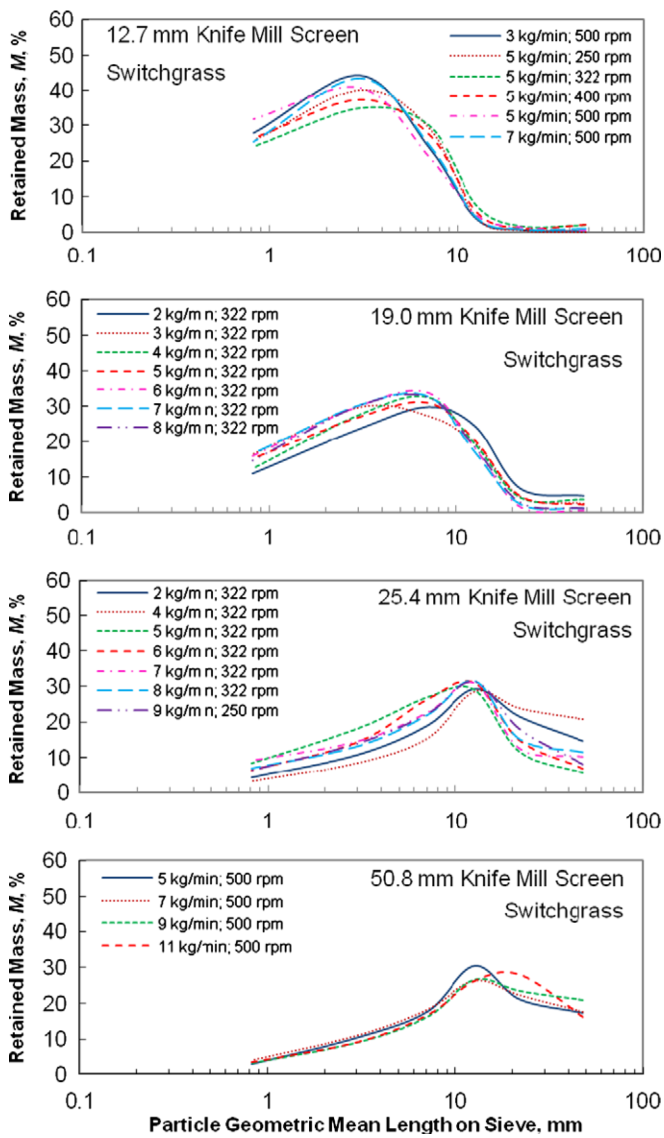

Fig. 2. Log-normal distribution of switchgrass chopped particles for different knife mill screens (all combinations of mass flow rate and knife mill speed are not shown).

Generally, uniformity index and size guide number of particle size distribution are determined using the procedure of Canadian Fertilizer Institute (CFI, 1982). Uniformity index is the ratio of particle sizes 'small' (D_5) to 'large' (D_{95}) in the product, expressed in percentage. Size guide number is the median dimension expressed in mm to the second decimal and then multiplied by 100 (CFI, 1982). These calculations are prone to positive and negative errors due to linear interpolation (Perfect and Xu, 1998). Due to this limitation, in the present study, uniformity index and size guide number were assessed from:

$$I_u = 100\,e^{-3.80423/b} \quad (8)$$

where, I_u is uniformity index, %; and b is Rosin–Rammler distribution parameter.

Size guide number was derived as:

$$N_{sg} = 100\,D_p = 100\,D_{50} \quad (9)$$

where, N_{sg} is size guide number (dimensionless); D_p is particle size, mm; and D_{50} is median length, mm.

Substituting M_{cu} = 50 and $D_p = D_{50}$ in Eq. (3), median length, D_{50}, was arrived as:

$$D_{50} = a\,e^{-0.366513/b}$$

where, a is Rosin–Rammler size parameter, mm; and b is Rosin–Rammler distribution parameter.

Then, from Eq. (9):

$$N_{sg} = 100a\,e^{-0.366513/b} = 100\,a(0.69314718)^{1/b} \quad (10)$$

Coefficient of uniformity and coefficient of gradation of particle size distribution (Craig, 2004) were evaluated as follows:

$$C_u = D_{60}/D_{10} \quad (11)$$

$$C_g = D_{30}^2/(D_{10} \times D_{60}) \quad (12)$$

where, C_u is coefficient of uniformity (dimensionless); C_g is coefficient of gradation (dimensionless); D_{10} is effective size, mm; and D_{30} and D_{60} are particle sizes in mm corresponding to 30% and 60% cumulative undersize mass, respectively.

Distribution geometric standard deviation of high region (between D_{84} and D_{50}), geometric standard deviation of low region (between D_{16} and D_{50}), and geometric standard deviation of the total region (between D_{84} and D_{16}) (Hinds, 1982) were determined as follows:

$$GSD_1 = D_{84}/D_{50} \quad (13)$$

$$GSD_2 = D_{50}/D_{16} \quad (14)$$

$$GSD_{12} = \sqrt{(D_{84}/D_{16})} \quad (15)$$

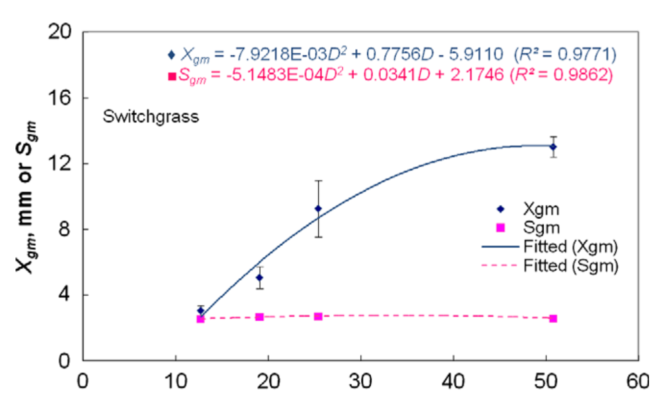

Fig. 3. Variation in geometric mean length (X_{gm}) and geometric standard deviation (S_{gm}) of switchgrass chopped particles with knife mill screen size (error bars represent standard deviation from the mean.)

Table 1
Estimated values of geometric mean length, geometric standard deviation, and parameters of Rosin–Rammler equation and its coefficient of determination for knife mill size reduction of switchgrass.

Mass feed rate, F, kg/min	Mill speed, N, rpm	Geometric mean length, X_{gm}, mm[a]	Geometric standard deviation, S_{gm}[a]	Rosin–Rammler size parameter, a, mm[a]	Rosin–Rammler distribution parameter, b[a]	Coefficient of determination, R^2
Knife mill screen size = 12.7 mm						
3	500	2.77 r	2.37 b	4.29 s	1.23 abcdefgh	0.993
5	250	3.00 qr	2.40 ab	4.73 s	1.26 abcdefgh	0.984
5	322	3.49 opqr	2.69 ab	5.49 qrs	1.18 defgh	0.982
5	400	3.17 qr	2.65 ab	4.94 s	1.16 efgh	0.985
5	450	3.30 pqr	2.52 ab	5.08 rs	1.29 abcdefgh	0.990
5	500	2.65 r	2.51 ab	4.11 s	1.09 h	0.994
7	500	2.99 qr	2.47 ab	4.60 s	1.25 abcdefgh	0.993
Knife mill screen size = 19.0 mm						
2	322	6.24 jklm	2.72 ab	9.62 mn	1.31 abcdefgh	0.990
2	500	6.29 jkl	2.78 ab	9.75 mn	1.24 abcdefgh	0.991
3	322	4.77 lmnopq	2.78 ab	7.62 op	1.20 cdefgh	0.994
3	500	5.33 lmn	2.69 ab	8.24 nop	1.31 abcdefgh	0.992
4	322	5.41 lmn	2.66 ab	8.20 nop	1.37 abcdefgh	0.987
4	500	5.55 lmn	2.66 ab	8.61 mnop	1.30 abcdefgh	0.992
5	250	4.39 nopqr	2.66 ab	7.04 pq	1.26 abcdefgh	0.993
5	322	5.04 lmnop	2.70 ab	7.98 nop	1.29 abcdefgh	0.989
5	400	5.34 lmn	2.63 ab	8.25 nop	1.37 abcdefgh	0.990
5	450	4.70 lmnopq	2.45 ab	7.26 opq	1.53 ab	0.992
5	500	4.20 nopqr	2.78 ab	6.80 pqr	1.14 gh	0.992
6	322	4.45 mnopqr	2.50 ab	7.03 pq	1.47 abcde	0.988
6	500	4.21 nopqr	2.77 ab	6.82 pqr	1.15 fgh	0.993
7	322	4.45 mnopqr	2.58 ab	7.01 pq	1.38 abcdefgh	0.988
7	500	5.21 lmno	2.57 ab	8.03 nop	1.43 abcdefg	0.992
8	322	4.70 lmnopq	2.54 ab	7.30 opq	1.43 abcdefg	0.990
8	500	5.77 klmn	2.65 ab	8.97 mno	1.37 abcdefgh	0.991
Knife mill screen size = 25.4 mm						
2	322	11.86 cd	2.62 ab	17.42 e	1.45 abcdefg	0.997
2	500	8.39 fgh	2.84 ab	12.97 ghijk	1.26 abcdefgh	0.990
4	322	14.19 a	2.56 ab	20.25 a	1.52 ab	0.997
4	500	9.43 efg	2.71 ab	14.22 fgh	1.34 abcdefgh	0.992
5	250	9.35 fgh	2.58 ab	13.89 fghi	1.38 abcdefgh	0.993
5	322	7.63 ghij	2.68 ab	11.74 kl	1.36 abcdefgh	0.994
5	400	8.97 fgh	2.65 ab	13.44 fghijk	1.40 abcdefg	0.995
5	450	8.19 fghi	2.72 ab	12.59 hijk	1.35 abcdefgh	0.993
5	500	8.77 fgh	2.63 ab	13.10 ghijk	1.44 abcdefg	0.994
6	322	8.85 fgh	2.57 ab	13.22 ghijk	1.45 abcdefg	0.993
6	500	11.22 de	2.86 ab	17.33 e	1.29 abcdefgh	0.996
7	250	7.55 hijk	2.80 ab	11.82 jkl	1.27 abcdefgh	0.995
7	322	8.65 fgh	2.89 a	13.57 fghij	1.29 abcdefgh	0.994
7	400	6.46 ijkl	2.81 ab	10.40 lm	1.23 bcdefgh	0.994
7	450	9.20 fgh	2.65 ab	13.86 fghi	1.35 abcdefgh	0.993
7	500	9.83 ef	2.78 ab	15.05 f	1.33 abcdefgh	0.995
8	322	9.70 ef	2.76 ab	14.76 fg	1.37 abcdefgh	0.996
8	500	8.32 fgh	2.52 ab	12.38 ijk	1.47 abcd	0.991
9	250	9.43 efg	2.64 ab	14.31 fgh	1.42 abcdefg	0.996
Knife mill screen size = 50.8 mm						
5	322	13.59 abc	2.54 ab	19.69 ab	1.47 abcd	0.991
5	500	12.79 abcd	2.55 ab	18.36 bcde	1.48 abcd	0.999
7	322	13.04 abcd	2.77 ab	19.60 abc	1.38 abcdefgh	0.997
7	500	12.38 abcd	2.50 ab	17.85 cde	1.50 abc	0.997
7	500	12.40 abcd	2.70 ab	18.47 abcde	1.38 abcdefgh	0.996
9	322	13.50 abc	2.55 ab	19.58 abc	1.47 abcd	0.991
9	500	13.92 ab	2.62 ab	20.18 ab	1.46 abcdef	0.997
11	500	13.32 abc	2.54 ab	19.28 abcd	1.54 a	0.993
n[b]		153	153	153	153	
SEM[b]		0.40	0.03	0.40	0.01	
CV[b]		5.79	5.79	5.79	5.79	
MSD[b]		1.83	0.50	1.83	0.31	
Mean sum square						
Screen size		183.438[c]	0.064[c]	374.455[c]	0.084[c]	
Speed		1.472[c]	0.008[c]	2.784[c]	0.008[c]	
Mass feed rate		1.820[c]	0.008[c]	3.042[c]	0.005[c]	

[a] Means with same letters in each column are not significantly different at $P < 0.05$ using Tukey's studentized range (HSD) test. Different letters within a value represent a significant difference.
[b] n – Number of observations; SEM – square error mean; CV – critical value; MSD – minimum significant difference.
[c] Significantly different at $P < 0.05$.

where, GSD_1, GSD_2, and GSD_{12} were distribution geometric standard deviation of high, low, and total regions, respectively; and D_{16}, D_{50}, and D_{84} are particle sizes in mm corresponding to 16%, 50%, and 84% cumulative undersize mass, respectively.

Table 2
Median length, effective size, mass relative span, inclusive graphic skewness, and graphic kurtosis for knife mill size reduction of switchgrass using different screens.

Mass feed rate, *F*, kg/min	Mill speed, *N*, rpm	Median length, D_{50}, mm[a]	Effective size, D_{10}, mm[a]	Mass relative span, RS_m[a]	Inclusive graphic skewness, GS_i[a]	Graphic kurtosis, K_g[a]
Knife mill screen size = 12.7 mm						
3	500	3.19 rs	0.69 pq	2.43 abcdef	0.36 abcdefg	1.02 abcdef
5	250	3.54 pqrs	0.79 opq	2.36 abcdef	0.35 abcdefg	1.02 abcdef
5	322	4.02 nopqrs	0.81 opq	2.57 abcd	0.39 abcde	1.04 abcd
5	400	3.60 pqrs	0.71 pq	2.63 abc	0.39 abcd	1.04 abc
5	450	3.82 opqrs	0.89 nopq	2.30 abcdef	0.34 abcdefg	1.01 bcdef
5	500	2.93 s	0.52 q	2.83 a	0.42 a	1.06 a
7	500	3.43 qrs	0.76 pq	2.39 abcdef	0.35 abcdefg	1.02 abcdef
Knife mill screen size = 19.0 mm						
2	322	7.27 ijkl	1.72 ijklmnopq	2.27 abcdef	0.33 abcdefg	1.01 bcdef
2	500	7.25 ijkl	1.58 jklmnopq	2.42 abcdef	0.36 abcdefg	1.02 abcdef
3	322	5.62 lmno	1.18 mnopq	2.50 abcde	0.37 abcdef	1.03 abcde
3	500	6.22 klm	1.47 klmnopq	2.27 abcdef	0.33 abcdefg	1.01 bcdef
4	322	6.28 klm	1.58 jklmnopq	2.16 bcdef	0.31 bcdefg	1.00 bcdef
4	500	6.49 klm	1.52 klmnopq	2.29 abcdef	0.34 abcdefg	1.01 bcdef
5	250	5.26 lmnopq	1.18 mnopq	2.37 abcdef	0.35 abcdefg	1.02 abcdef
5	322	6.01 klmn	1.40 lmnopq	2.30 abcdef	0.34 abcdefg	1.01 bcdef
5	400	6.32 klm	1.60 jklmnopq	2.14 bcdef	0.31 bcdefg	1.00 cdef
5	450	5.71 klmno	1.67 ijklmnopq	1.90 f	0.26 g	0.98 f
5	500	4.93 mnopqrs	0.95 nopq	2.66 ab	0.40 ab	1.05 ab
6	322	5.47 lmnop	1.51 klmnopq	1.99 ef	0.28 efg	0.99 ef
6	500	4.96 mnopqr	0.96 nopq	2.66 ab	0.40 abc	1.04 ab
7	322	5.38 lmnopq	1.38 lmnopq	2.13 bcdef	0.31 bcdefg	1.00 cdef
7	500	6.22 klm	1.67 ijklmnopq	2.04 def	0.29 defg	0.99 def
8	322	5.66 lmno	1.52 klmnopq	2.04 def	0.29 defg	0.99 def
8	500	6.86 jklm	1.73 ijklmnopq	2.16 bcdef	0.31 bcdefg	1.00 bcdef
Knife mill screen size = 25.4 mm						
2	322	13.53 cd	3.69 abcdefg	2.02 def	0.29 efg	0.99 def
2	500	9.69 fgh	2.17 ijklmno	2.37 abcdef	0.35 abcdefg	1.02 abcdef
4	322	15.92 a	4.62 a	1.91 f	0.26 g	0.98 f
4	500	10.81 fg	2.64 efghijkl	2.21 bcdef	0.32 abcdefg	1.00 bcdef
5	250	10.65 fg	2.71 defghijkl	2.14 bcdef	0.31 bcdefg	1.00 cdef
5	322	8.96 ghi	2.23 hijklmn	2.17 bcdef	0.32 bcdefg	1.00 bcdef
5	400	10.35 fg	2.71 defghijkl	2.09 cdef	0.30 bcdefg	0.99 cdef
5	450	9.60 fgh	2.38 ghijklm	2.18 bcdef	0.32 abcdefg	1.00 bcdef
5	500	10.15 fg	2.73 defghijkl	2.04 def	0.29 defg	0.99 def
6	322	10.27 fg	2.80 defghijk	2.01 def	0.29 efg	0.99 def
6	500	13.05 de	3.04 bcdefghi	2.30 abcdef	0.34 abcdefg	1.01 bcdef
7	400	7.72 hijk	1.67 ijklmnopq	2.44 abcdef	0.36 abcdefg	1.02 abcdef
7	450	10.56 fg	2.61 fghijkl	2.19 bcdef	0.32 abcdefg	1.00 bcdef
7	500	11.42 ef	2.77 defghijkl	2.23 bcdef	0.33 abcdefg	1.01 bcdef
7	322	11.29 ef	2.84 cdefghijk	2.16 bcdef	0.31 bcdefg	1.00 bcdef
7	250	8.85 ghij	2.00 ijklmnop	2.35 abcdef	0.35 abcdefg	1.02 abcdef
8	322	10.22 fg	2.38 ghijklm	2.30 abcdef	0.34 abcdefg	1.01 bcdef
8	500	9.65 fgh	2.67 defghijkl	1.99 ef	0.28 efg	0.99 ef
9	250	11.06 ef	2.95 bcdefghij	2.06 cdef	0.29 cdefg	0.99 def
Knife mill screen size = 50.8 mm						
5	322	15.35 abc	4.28 ab	1.98 def	0.28 efg	0.99 def
5	500	14.34 abcd	4.02 abcde	1.97 ef	0.28 fg	0.99 ef
7	322	15.04 abcd	3.85 abcdef	2.13 bcdef	0.31 bcdefg	1.00 bcdef
7	500	13.97 abcd	3.96 abcdef	1.95 ef	0.27 fg	0.99 ef
7	500	14.15 abcd	3.60 abcdefgh	2.14 bcdef	0.31 bcdefg	1.00 bcdef
9	322	15.25 abc	4.22 abc	1.99 def	0.28 efg	0.99 def
9	500	15.69 ab	4.30 ab	2.01 def	0.29 efg	0.99 def
11	500	15.20 abc	4.48 a	1.88 f	0.26 g	0.98 f
n[b]		153	153	153	153	153
SEM[b]		0.49	0.23	0.04	0.001	0.0003
CV[b]		5.79	5.79	5.79	5.79	5.79
MSD[b]		2.02	1.39	0.57	0.11	0.05
Mean sum square						
Screen size		231.843[c]	19.364[c]	0.331[c]	0.010[c]	0.0022[c]
Speed		1.405[c]	0.173[c]	0.039[c]	0.001[c]	0.0003[c]
Mass feed rate		2.593[c]	0.274[c]	0.015	0.001	0.0001

[a] Means with same letters in each column are not significantly different at $P < 0.05$ using Tukey's studentized range (HSD) test. Different letters within a value represent a significant difference.
[b] *n* – Number of observations; SEM – square error mean; CV – critical value; MSD – minimum significant difference.
[c] Significantly different at $P < 0.05$.

SAS ANOVA with Tukey analysis was performed on particle size distribution parameters data for mean separation. Pearson correlation coefficients among knife mill operating factors, geometric mean length, geometric standard deviation, Rosin–Rammler parameters, median length, effective length, mass relative span, uniformity index, size guide number, uniformity coefficient, and

Table 3
Uniformity index, size guide number, uniformity coefficient, coefficient of gradation and distribution geometric standard deviation for knife mill size reduction of switchgrass using different screens.

Mass feed rate, *F*, kg/min	Mill speed, *N*, rpm	Uniformity index, I_u, %[a]	Size guide number, N_{sg}[a]	Uniformity coefficient, C_u[a]	Coefficient of gradation, C_g[a]	GSD_1	GSD_2	GSD_{12}
Knife mill screen size = 12.7 mm								
3	500	4.57 bcdefg	319 rs	5.78 abcdefg	1.25 abcdef	2.20	3.06	2.60
5	250	4.91 abcdefg	354 pqrs	5.55 abcdefg	1.24 abcdef	2.16	2.99	2.54
5	322	3.95 defg	402 nopqrs	6.29 abcde	1.26 abcd	2.28	3.23	2.72
5	400	3.72 efg	360 pqrs	6.49 abcd	1.27 abc	2.32	3.30	2.77
5	450	5.26 abcdefg	382 opqrs	5.34 bcdefg	1.24 abcdef	2.12	2.91	2.49
5	500	3.06 g	293 s	7.26 a	1.29 a	2.44	3.54	2.94
7	500	4.78 abcdefg	343 qrs	5.63 abcdefg	1.25 abcdef	2.17	3.01	2.56
Knife mill screen size = 19.0 mm								
2	322	5.46 abcdefg	727 ijkl	5.23 bcdefg	1.23 abcdef	2.10	2.87	2.46
2	500	4.63 abcdefg	725 ijkl	5.73 abcdefg	1.25 abcdef	2.19	3.05	2.58
3	322	4.25 cdefg	562 lmno	6.02 abcdef	1.26 abcde	2.24	3.14	2.65
3	500	5.45 abcdefg	622 klm	5.23 bcdefg	1.23 abcdef	2.10	2.87	2.46
4	322	6.17 abcdefg	627 klm	4.87 bcdefg	1.22 bcdef	2.04	2.75	2.37
4	500	5.34 abcdefg	649 klm	5.29 bcdefg	1.24 abcdef	2.11	2.90	2.47
5	250	4.85 abcdefg	526 lmnopq	5.59 abcdefg	1.25 abcdef	2.17	3.00	2.55
5	322	5.26 abcdefg	601 klmn	5.33 bcdefg	1.24 abcdef	2.12	2.91	2.49
5	400	6.29 abcdefg	632 klm	4.82 cdefg	1.22 bcdef	2.03	2.73	2.35
5	450	8.29 ab	571 klmno	4.12 g	1.20 f	1.89	2.47	2.16
5	500	3.60 fg	493 mnopqrs	6.62 ab	1.27 ab	2.34	3.34	2.79
6	322	7.46 abcdef	547 lmnop	4.38 fg	1.21 def	1.94	2.56	2.23
6	500	3.62 fg	496 mnopqr	6.59 abc	1.27 ab	2.33	3.33	2.79
7	322	6.38 abcdefg	538 lmnopq	4.78 defg	1.22 bcdef	2.02	2.71	2.34
7	500	7.05 abcdef	622 klm	4.52 efg	1.21 def	1.97	2.62	2.27
8	322	7.05 abcdef	566 lmno	4.52 efg	1.21 def	1.97	2.62	2.27
8	500	6.18 abcdefg	686 jklm	4.87 bcdefg	1.22 bcdef	2.04	2.75	2.37
Knife mill screen size = 25.4 mm								
2	322	7.25 abcdef	1353 cd	4.45 efg	1.21 def	1.96	2.59	2.25
2	500	4.86 abcdefg	969 fgh	5.58 abcdefg	1.25 abcdef	2.17	3.00	2.55
4	322	8.23 ab	1592 a	4.14 g	1.20 f	1.89	2.47	2.16
4	500	5.82 abcdefg	1081 fg	5.04 bcdefg	1.23 bcdef	2.07	2.81	2.41
5	250	6.32 abcdefg	1065 fg	4.81 defg	1.22 bcdef	2.03	2.72	2.35
5	322	6.06 abcdefg	896 ghi	4.92 bcdefg	1.23 bcdef	2.05	2.77	2.38
5	400	6.66 abcdefg	1035 fg	4.66 defg	1.22 bcdef	2.00	2.67	2.31
5	450	6.01 abcdefg	960 fgh	4.95 bcdefg	1.23 bcdef	2.05	2.77	2.39
5	500	7.08 abcdef	1015 fg	4.51 efg	1.21 def	1.97	2.61	2.27
6	322	7.27 abcdef	1027 fg	4.44 efg	1.21 def	1.95	2.59	2.25
6	500	5.27 abcdefg	1305 de	5.33 bcdefg	1.24 abcdef	2.12	2.91	2.48
7	250	4.97 abcdefg	885 ghij	5. 51 abcdefg	1.24 abcdef	2.15	2.97	2.53
7	322	5.28 abcdefg	1022 fg	5.33 bcdefg	1.24 abcdef	2.12	2.91	2.48
7	400	4.53 bcdefg	772 hijk	5.81 abcdefg	1.25 abcdef	2.21	3.07	2.60
7	450	5.94 abcdefg	1056 fg	4.98 bcdefg	1.23 bcdef	2.06	2.79	2.39
7	500	5.71 abcdefg	1142 ef	5.09 bcdefg	1.23 abcdef	2.08	2.83	2.42
8	322	6.17 abcdefg	1129 ef	4.87 bcdefg	1.22 bcdef	2.04	2.75	2.37
8	500	7.48 abcdef	965 fgh	4.37 fg	1.21 ef	1.94	2.56	2.23
9	250	6.91 abcdefg	1106 ef	4.57 efg	1.21 cdef	1.98	2.64	2.28
Knife mill screen size = 50.8 mm								
5	322	7.57 abcde	1535 abc	4.34 efg	1.21 def	1.93	2.55	2.22
5	500	7.67 abcd	1434 abcd	4.31 fg	1.20 ef	1.93	2.54	2.21
7	322	6.38 abcdefg	1504 abcd	4.78 bcdefg	1.22 bcdef	2.02	2.71	2.34
7	500	7.86 abc	1397 abcd	4.25 fg	1.20 ef	1.92	2.52	2.20
7	500	6.31 abcdefg	1415 abcd	4.81 bcdefg	1.22 bcdef	2.03	2.72	2.35
9	322	7.48 abcdef	1525 abc	4.37 efg	1.21 def	1.94	2.56	2.23
9	500	7.33 abcdef	1569 ab	4.42 efg	1.21 def	1.95	2.58	2.24
11	500	8.47 a	1520 abc	4.07 g	1.20 f	1.88	2.45	2.15
n[b]		153	153	153	153			
SEM[b]		1.83	4867.4	0.42	0.0003			
CV[b]		5.79	5.79	5.79	5.79			
MSD[b]		3.92	202.1	1.88	0.06			
Mean sum square								
Screen size		12.349[c]	2318614.0[c]	3.619[c]	0.0031[c]			
Speed		1.242[c]	18001.0[c]	0.402[c]	0.0003[c]			
Mass feed rate		0.807[c]	19499.0[c]	0.189	0.0002[c]			

[a] Means with same letters in each column are not significantly different at $P < 0.05$ using Tukey's studentized range (HSD) test. Different letters within a value represent a significant difference.
[b] *n* – Number of observations; SEM – square error mean; CV – critical value; MSD – minimum significant difference.
[c] Significantly different at $P < 0.05$.

distribution standard deviation were determined using PROC CORR procedure in (SAS, 2004). SAS Non-Linear Regression (NLIN) procedure and Generalized Linear Model (GLM) procedure (SAS, 2004) were used for all regression fits and analyses. Particle size distribution parameters were regressed as a function of screen size, mass feed rate, and rotor speed in second order polynomial equations after neglecting non-significant variables and their interactions. Statistical significance was set at $P < 0.05$ unless otherwise noted.

3. Results and discussion

3.1. Particle size analysis of knife mill size reduction of switchgrass

3.1.1. Size distribution

Switchgrass mass percent retained on each test sieve, M, in relation to geometric mean length of particles on each sieve followed log-normal distribution for all the knife mill screens (Fig. 2). But, all the distribution curves showed positive skewness or fine skewed (a tail to the right on normal scale of X-axis) for all screen sizes from 12.7 to 50.8 mm. Skewness could well be viewed if abscissa of Fig. 2 is drawn on normal scale as shown by Womac et al. (2007). About 27%, 15%, 10%, and 5% of switchgrass contained particle size <1 mm for 12.7, 19.0, 25.4, and 50.8 mm screens, respectively, which indicated that further size reduction was required to make it more suitable for effective chemical reactions. Different mean separations in particle size distribution curves were observed for four mill screens tested. Similar particle distribution trends were observed hammer mill grinds of wheat, soybean meal, corn (Pfost and Headley, 1976), alfalfa (Yang et al., 1996), wheat straw (Himmel et al., 1985; Mani et al., 2004a), corn stover (Himmel et al., 1985), switchgrass, and barley straw (Mani et al., 2004a).

3.1.2. Geometric mean length and geometric standard deviation

Average geometric mean length, X_{gm}, of switchgrass increased from 3.05 ± 0.29 to 13.01 ± 0.62 mm with an increase in knife mill screen size from 12.7 to 50.8 mm (Fig. 3). These coarse particles are suitable for boilers and ablative pyrolyzers (Lédé, 2003). A specific trend of mean length was not observed with increase in feed rate and speed for each screen (Table 1). Geometric mean length of switchgrass from ASABE sieve analysis results was less than the image analysis and micrometer readings measured by Yang (2007). ASABE sieve analysis gave an under sized geometric mean length due to slip down of lengthy particles onto lower sieves. Yang (2007) observed geometric mean length of 5× using image analysis and compared with micrometer readings. Geometric mean length was directly proportional to Rosin–Rammler size parameter (Table 1), median length and effective size (Table 2), and size guide number (Table 3). Mean separation of geometric mean length indicated significant difference ($P < 0.05$) in particle sizes between different screens (Table 1). Minimum significant difference (MSD) test across geometric mean length resulted in similar and coherent mean separations. In other words, geometric mean lengths of particles resulted from 12.7, 19.0, and 50.8 mm screens were uniform individually for all feed rates and speeds. Variation in knife mill screen size, speed, and mass feed rate had significant effect ($P < 0.05$) on geometric mean length (Table 1). A positive correlation of 0.872 was established between geometric mean length, X_{gm}, and knife mill screen size, D, and there was weak correlation between geometric mean length and feed rate, F (0.349) and knife mill speed, N (0.037) (Table 4).

Average geometric standard deviation, S_{gm}, 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 (Fig. 3). For normal distribution curve, one standard deviation represents difference between size associated with a cumulative count of 84.1% and median (50% cumulative count) size (or between 50% cumulative size and 15.9% cumulative size) and standard deviation must always be greater than or equal to 1.0 (Hinds, 1982) (Table 1). Higher standard deviation than 1.0 represented wider distribution of particles. Geometric standard deviation indicated only two mean separations (Table 1). In other words, 12.7, 19.0, and 50.8 mm screens formed small standard deviation curves and 25.4 mm screen formed distribution curves with large standard deviation. Geometric standard deviation of particles was similar for each screen individually with minor variations when feed rate and speed were altered. Hence, values of geometric mean length and standard deviation of each screen were averaged and they were represented as a function of screen size, D, with very high coefficient of determination ($R^2 > 0.97$) (Fig. 3). Variation in knife mill screen size, speed, and mass feed rate had significant effect ($P < 0.05$) on geometric standard deviation (Table 1). Geometric standard deviation had little correlation with knife mill operating factors (Table 4).

3.1.3. Cumulative size distribution

Switchgrass cumulative undersize mass percentage as a function of particle diagonal sieve opening size was not linear when plotted as log-probability graph (Fig. 4), which indicated bimodal distribution of particles (Hinds, 1982). Further, there was no optical and aerodynamic cutoff observed on log–log scale (not shown) as particles were lengthy in size. Optical and aerodynamic cutoff of size distribution means curving down of lower end and curving up of upper end of log-probability curve, respectively (Hinds, 1982). Coarse particles larger than 26.9 mm (large sieve) were about 2%, 4%, 10%, and 16% for 12.7, 19.0, 25.4, and 50.8 mm screen sizes, respectively. Overall, cumulative trends for screen sizes from 12.7 to 50.8 mm were said to be 'well-graded', even though the gap- or step-graded distribution was observed for 12.7 mm screen size for particles >10 mm, and a partial 'poorly-graded' distribution was observed for particles between 5.6 and 9.0 mm.

3.1.4. Rosin–Rammler parameters

Rosin–Rammler parameters considered 100% of the particle mass. Average Rosin–Rammler size parameter, a, an intercept of equation, increased from 4.75 ± 0.47 to 18.94 ± 0.93 mm with an increase in screen size from 12.7 to 50.8 mm (Fig. 5). Size parameter was always greater than median length, which was greater than geometric mean length (Tables 1 and 2). This trend was due to positive skewness (fine skewed) of distribution, median length determined from fitted curvilinear trend, and geometric mean calculated based on linear portion of the data points (Perfect and Xu, 1998). Geometric mean of particles moved to the right with an increase in size parameter, resulting in a mix of reduced fines and increased coarse particles (Table 1). Variation in knife mill screen size, speed, and mass feed rate had significant effect ($P < 0.05$) on Rosin–Rammler size parameter (Table 1). Rosin–Rammler size parameter had strong correlation with screen size (0.863) and weak correlation with feed rate and speed (Table 4).

Average Rosin–Rammler distribution parameter, b (slope), increased from 1.21 ± 0.07 to 1.47 ± 0.06 with an increase in screen size from 12.7 to 50.8 mm (Fig. 5). Further, increased distribution parameter represented more uniformity of particles. For example, distribution curve of 50.8 mm, 9 kg/min, 322 rpm ($b = 1.47$) was more uniform than 50.8 mm, 7 kg/min, 322 rpm ($b = 1.38$) even though they have equal Rosin–Rammler size parameter of 19.6 mm (Table 1). Thus, kurtosis values (Table 2) were inversely proportional to distribution parameter (Table 1) and directly proportional to mass relative span (Table 2). This means that a reduced distribution parameter indicated increased distribution. Hence, each chop produced using varied knife mill operating factors was different in distribution, and distributions were sensitive to proportion of fine and coarse particles (Djamarani and Clark, 1997). In all cases, Rosin–Rammler equations fit with a high $R^2 > 0.982$. This agrees with published trends (Allaire and Parent,

Table 4
Pearson correlation coefficients for knife mill size reduction of switchgrass.

Parameter	Screen size, D, mm	Mass feed rate, F, kg/min	Speed, N, rpm	Geometric mean length, X_{gm}, mm	Geometric standard deviation, S_{gm}	Rosin–Rammler size parameter, a, mm	Rosin–Rammler distribution parameter, b	Median diameter, D_{50}, mm	Effective size, D_{10}, mm	Mass relative span, RS_m	Uniformity index, I_u, %	Size guide number, N_{sg}	Uniformity coefficient, C_u	Coefficient of gradation, C_g	Distribution standard deviation (higher), GSD_1	Distribution standard deviation (lower), GSD_2	Distribution standard deviation (total), GSD_{12}
D	1.000																
F	0.486 (3E-4)	1.000															
N	0.124 (0.381)	0.0527 (0.711)	1.000														
X_{gm}	0.872 (<10^{-4})	0.349 (0.011)	0.037 (0.796)	1.000													
S_{gm}	−0.042 (0.770)	−0.164 (0.247)	−0.032 (0.824)	0.096 (0.500)	1.000												
a	0.863 (<10^{-4})	0.348 (0.012)	0.030 (0.835)	0.998 (<10^{-4})	0.143 (0.311)	1.000											
b	0.605 (<10^{-4})	0.411 (0.003)	−0.042 (0.766)	0.661 (<10^{-4})	−0.416 (0.002)	0.642 (<10^{-4})	1.000										
D_{50}	0.868 (<10^{-4})	0.357 (0.009)	0.028 (0.841)	0.999 (<10^{-4})	0.112 (0.429)	0.999 (<10^{-4})	0.666 (<10^{-4})	1.000									
D_{10}	0.876 (<10^{-4})	0.393 (0.004)	0.026 (0.853)	0.989 (<10^{-4})	−0.022 (0.878)	0.982 (<10^{-4})	0.754 (<10^{-4})	0.988 (<10^{-4})	1.000								
RS_m	−0.582 (<10^{-4})	−0.386 (0.005)	0.071 (0.617)	−0.654 (<10^{-4})	0.370 (0.007)	−0.639 (<10^{-4})	−0.992 (<10^{-4})	−0.661 (<10^{-4})	−0.740 (<10^{-4})	1.000							
I_u	0.610 (<10^{-4})	0.418 (0.002)	−0.033 (0.818)	0.661 (<10^{-4})	−0.430 (0.002)	0.641 (<10^{-4})	0.999 (<10^{-4})	0.665 (<10^{-4})	0.756 (<10^{-4})	−0.986 (<10^{-4})	1.000						
N_{sg}	0.868 (<10^{-4})	0.357 (0.009)	0.028 (0.841)	0.999 (<10^{-4})	0.112 (0.429)	0.999 (<10^{-4})	0.666 (<10^{-4})	1.000 (<10^{-4})	0.988 (<10^{-4})	−0.661 (<10^{-4})	0.665 (<10^{-4})	1.000					
C_u	−0.571 (<10^{-4})	−0.373 (0.006)	0.082 (0.563)	−0.647 (<10^{-4})	0.349 (0.011)	−0.634 (<10^{-4})	−0.984 (<10^{-4})	−0.655 (<10^{-4})	−0.730 (<10^{-4})	0.999 (<10^{-4})	−0.976 (<10^{-4})	−0.655 (<10^{-4})	1.000				
C_g	−0.587 (<10^{-4})	−0.390 (0.004)	0.067 (0.638)	−0.656 (<10^{-4})	0.378 (0.006)	−0.640 (<10^{-4})	−0.994 (<10^{-4})	−0.663 (<10^{-4})	−0.743 (<10^{-4})	1.000 (<10^{-4})	−0.989 (<10^{-4})	−0.663 (<10^{-4})	0.997 (<10^{-4})	1.000			
GSD_1	−0.581 (<10^{-4})	−0.384 (0.005)	0.072 (0.610)	−0.653 (<10^{-4})	0.367 (0.007)	−0.638 (<10^{-4})	−0.991 (<10^{-4})	−0.660 (<10^{-4})	−0.739 (<10^{-4})	1.000 (<10^{-4})	−0.985 (<10^{-4})	−0.660 (<10^{-4})	0.999 (<10^{-4})	1.000 (<10^{-4})	1.000		
GSD_2	−0.577 (<10^{-4})	−0.380 (0.005)	0.076 (0.594)	−0.651 (<10^{-4})	0.361 (0.009)	−0.637 (<10^{-4})	−0.989 (<10^{-4})	−0.659 (<10^{-4})	−0.736 (<10^{-4})	1.000 (<10^{-4})	−0.982 (<10^{-4})	−0.659 (<10^{-4})	1.000 (<10^{-4})	0.999 (<10^{-4})	1.000 (<10^{-4})	1.000	
GSD_{12}	−0.579 (<10^{-4})	−0.382 (0.005)	0.074 (0.602)	−0.652 (<10^{-4})	0.364 (0.008)	−0.638 (<10^{-4})	−0.990 (<10^{-4})	−0.659 (<10^{-4})	−0.737 (<10^{-4})	1.000 (<10^{-4})	−0.983 (<10^{-4})	−0.659 (<10^{-4})	0.999 (<10^{-4})	0.999 (<10^{-4})	1.000 (<10^{-4})	1.000 (<10^{-4})	1.000

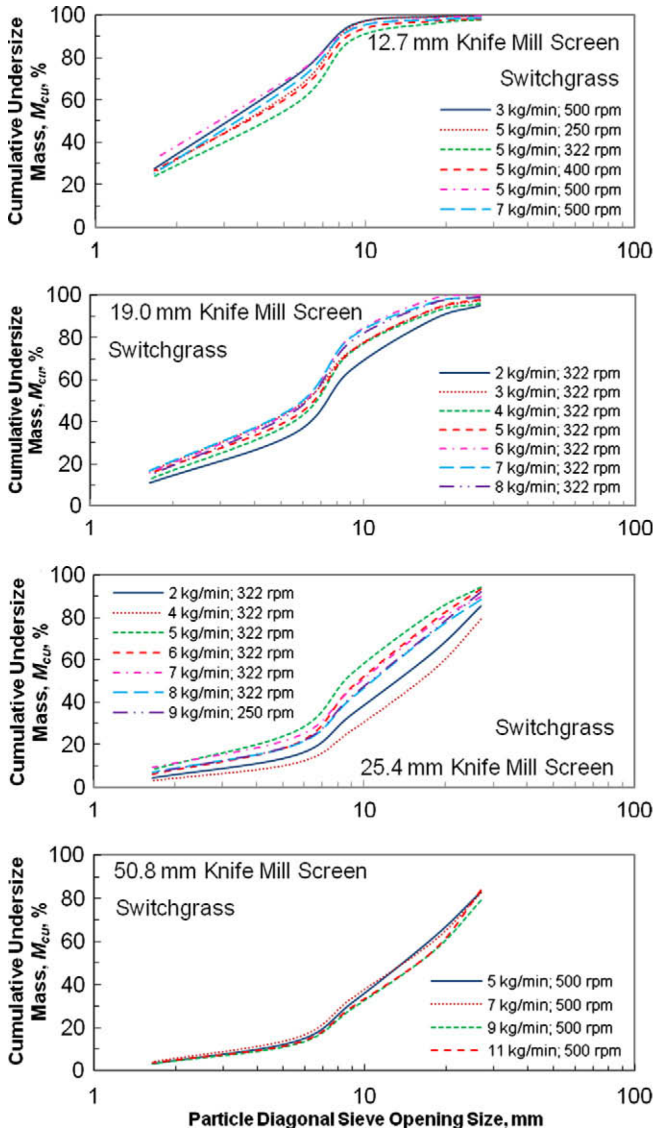

Fig. 4. Cumulative percent undersize switchgrass chopped particles for different knife mill screens (all combinations of mass flow rate and knife mill speed are not shown).

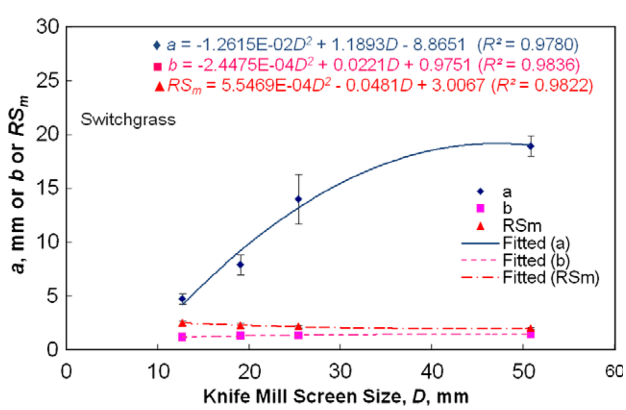

Fig. 5. Variation in Rosin–Rammler size (a) and distribution (b) parameters and relative span (RS_m) with knife mill screen size for switchgrass chopped particles (error bars represent standard deviation from the mean).

2003; Jaya and Durance, 2007; Perfect and Xu, 1998). Increased coefficient of determination indicated that particle size distribution of switchgrass was well-fit by Rosin–Rammler function, perhaps attributed to the fact that Rosin–Rammler expression was well suited to skewed distribution of particle sizes. Skewed distributions occur when significant quantities of particles, either in higher or lower region, exist or are removed from the region of predominant size (Djamarani and Clark, 1997). Variation in knife mill screen size, speed, and mass feed rate had significant effect ($P < 0.05$) on Rosin–Rammler distribution parameter (Table 1). Distribution parameter had moderate correlation with screen size (0.605) and weak correlation with feed rate and speed (Table 4).

3.1.5. Median length, effective size and mass relative span

Average median lengths, D_{50}, were 3.50 ± 0.37, 5.99 ± 0.72, 10.72 ± 1.85, and 14.75 ± 0.70 mm for 12.7, 19.0, 25.4, and 50.8 mm screens, respectively (Table 2). Median length was greater than geometric mean length (Tables 1 and 2) due to fine skewness of the distribution. Mean separation of median length indicated fairly uniform particle length for each screen. Median length had strong correlation with screen size (0.868) and weak correlation with feed rate and speed (Table 4). Effective size was less than median length as it should be mathematically (Table 2). Average effective sizes, D_{10}, were 0.74 ± 0.12, 1.45 ± 0.25, 2.72 ± 0.63, and 4.08 ± 0.27 mm for 12.7, 19.0, 25.4, and 50.8 mm screens, respectively. Mean separation of effective size indicated nearly uniform particle size for each screen. Effective size had strong correlation with screen size (0.876) and weak correlation with feed rate and speed (Table 4). Variation in knife mill screen size, speed, and mass feed rate had significant effect ($P < 0.05$) on median length and effective size (Table 2).

Average mass relative span, RS_m, decreased from 2.50 ± 0.18 to 1.99 ± 0.09 with an increase in screen size from 12.7 to 50.8 mm (Fig. 5). Mass relative span, which accounted for 80% particle mass, varied without any specific trend with respect to feed rate and rpm of mill for each knife mill screen. Decrease in span indicated narrow distribution of particles and also skewness decreased with an increase in screen size from 12.7 to 50.8 mm. It was also noted that relative span was inversely proportional to Rosin–Rammler distribution parameter. But, span was greater than 1.0, which indicated a wide distribution of particles. Himmel et al. (1985) also observed wide distribution of wheat straw grind and aspen chips prepared with small screens. Mean separation of span indicated uniform size distributed particles with the least number (six) of coherent groups. Variation in knife mill screen size and speed had significant effect ($P < 0.05$) on mass relative span (Table 2). Mass relative span had moderate negative correlation with screen size (−0.582) and weak correlation with feed rate and speed (Table 4). Keeping in view the similarity of chops for each screen size, regression analysis of average values of Rosin–Rammler parameters and mass relative span as a function of screen size, D, gave high coefficient of determination of 0.98 (Fig. 5).

3.1.6. Skewness and kurtosis

Selection of knife mill screen size affected the characteristic shape of particle spectra curves (Fig. 2). Average inclusive graphic skewness, GS_i, decreased with an increase in screen size (Table 2). Screen sizes of 12.7, 19.0, and 25.4 mm yielded 'strongly fine skewed' particles with GS_i between +1.0 and +0.3, whereas 50.8 mm screen resulted in 'fine skewed' particles (GS_i: +0.3 to +0.1) (Folk, 1974). Mean separation of skewness followed fairly similar grouping of relative span (Table 2). Average graphic kurtosis, K_g, values were 1.030 ± 0.018, 1.009 ± 0.018, 1.001 ± 0.011, and 0.988 ± 0.006 for 12.7, 19.0, 25.4, and 50.8 mm screens, respectively, which indicated kurtosis or peakedness decreased with increase in screen size (Table 2). Uniformity index of switchgrass particles increased with screen size (Table 3). Increased uniformity had increased Rosin–Rammler distribution parameter and decreased mass relative span as screen size increased. Switchgrass particles from all screens were termed as 'mesokurtic', as kurtosis was within 0.90 and 1.11 (Folk, 1974). Mesokurtic distribution is a distribution with a same degree of peakedness about the mean as a normal distribution. Hence, knife mill chopping of switchgrass resulted in 'strongly fine skewed mesokurtic' particles with reduced size screens (12.7–25.4 mm) and 'fine skewed mesokurtic' particles with increased size screen (50.8 mm). Variation in knife mill screen size and speed had significant effect ($P < 0.05$) on skewness and kurtosis (Table 2).

3.1.7. Uniformity index, size guide number, uniformity coefficient and coefficient of gradation

Average uniformity index, I_u, increased from 4.32 ± 0.77 to 7.50 ± 0.76% with an increase in screen size from 12.7 to 50.8 mm (Fig. 6). The reason was attributed to a decrease in relative span and skewness as screen size increased. Uniformity index of particle size distribution, which considered 85% of particle mass, was very low (<80%) for all samples (Table 3), due to strong fine skewness of particles. Mean separation of uniformity index was uniform for each knife mill screen tested. Correlation was moderate between uniformity index and screen size, D, (0.610), and weak with feed rate, F, (0.418) and speed, N (−0.033) (Table 4). Average size guide number, N_{sg}, increased from 350 ± 36 to 1475 ± 70 with an increase in screen size from 12.7 to 50.8 mm (Fig. 6). Size guide number had mean separation similar to median length, as it differed by a factor of 100 (Tables 2 and 3). Guide number had strong correlation with screen size (0.868) and weak correlation with feed rate (0.357) and speed (0.028) (Table 4). Variation in knife mill screen size, speed, and mass feed rate had significant effect ($P < 0.05$) on uniformity index and size guide number (Table 3).

Average uniformity coefficient, C_u, decreased from 6.05 ± 0.67 to 4.38 ± 0.26 with an increase in screen size from 12.7 to 50.8 mm (Fig. 6). Material with a uniformity coefficient of <4.0 contains particles of approximately uniform size (Budhu, 2007). Uniformity coefficient was more than 4.0 in all cases, which indicated a wide particle size range. This also represented a well-graded particle size distribution as indicated by gradually increasing cumulative distribution curve (Fig. 4). Uniformity coefficient, which accounted for 50% of particle mass, was inversely proportional to uniformity index (Table 3) with a correlation coefficient of −0.976 (Table 4). Mean separation of uniformity coefficient resulted in seven similar groups; however, it was uniformly mean separated for screen sizes together from 19.0 to 50.8 mm and separately for 12.7 mm screen. Allaire and Parent (2003) also found uniformity coefficient as the least discriminating distribution parameter. Variation in knife mill screen size and speed had significant effect ($P < 0.05$) on uniformity coefficient (Table 3). Uniformity coefficient had moderate negative correlation with screen size, D (−0.571), and weak correlation with feed rate, F, and speed, N (Table 4).

Average coefficient of gradation, C_g, which accounted for 50% of particle mass, decreased from 1.26 ± 0.02 to 1.21 ± 0.01 with an increase in screen size from 12.7 to 50.8 mm (Fig. 6). Coefficient of gradation between 1 and 3 represents well-graded particles (Budhu, 2007). Mean separation of coefficient of gradation resulted in least number (six) of uniform groups like relative span (Tables 2 and 3) as correlation coefficient was 1.0 between coefficient of gradation and relative span (Table 4). Variation in knife mill screen size, speed, and mass feed rate had significant effect ($P < 0.05$) on coefficient of gradation (Table 3). Coefficient of gradation had moderate negative correlation with screen size, D (−0.587), and weak relation with feed rate, F, and speed, N (Table 4).

3.1.8. Distribution geometric standard deviation

Bimodal distribution between cumulative undersize mass and particle length was observed on log–log plots (Fig. 4). Average distribution geometric standard deviation of total region, GSD_{12}, decreased gradually from 2.66 ± 0.16 to 2.23 ± 0.07 with an increase in screen size, D, from 12.7 to 50.8 mm (Fig. 7). Distribution geometric standard deviation of high region, GSD_1, and low region, GSD_2, also decreased with screen size. Distribution geometric standard deviation had moderate negative correlation with screen size, D (−0.579), and weak relation with feed rate, F, and speed, N (Table 4). Hence, use of distribution geometric standard deviation improved the relation with screen size, compared to using geometric standard deviation.

3.2. Correlations

A direct consistent relation was observed among size-related parameters, namely, geometric mean length, X_{gm}, Rosin–Rammler size parameter, a, median length, D_{50}, effective size, D_{10}, and size guide number, N_{sg}, as screen size was the predominant knife mill operating factor. The moments method used for calculation of geometric mean length accounted for the variability in the fractions retained on each sieve. Sieve retained mass data were the basis for estimation of a, D_{50}, D_{10}, and N_{sg}. Hence, strong correlation was established among size-related parameters. A strong positive correlation existed among distribution-related parameters, namely, mass relative span, RS_m, uniformity coefficient, C_u, coefficient of gradation, C_g, and distribution geometric standard deviation, GSD, and also among Rosin–Rammler distribution parameter, b, and uniformity index, I_u. These two sets of distribution-related parameters had negative correlation. Strong positive correlation among distribution-related parameters represented the shape of chopped

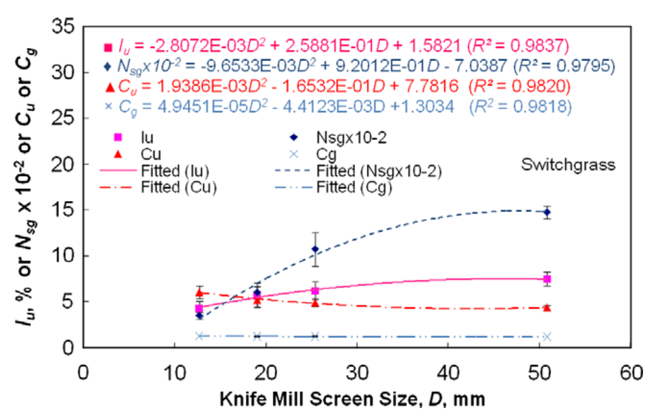

Fig. 6. Variation in uniformity index (I_u), size guide number (N_{sg}), coefficient of uniformity (C_u), and coefficient of gradation (C_g) with knife mill screen size for switchgrass chopped particles (error bars represent standard deviation from the mean).

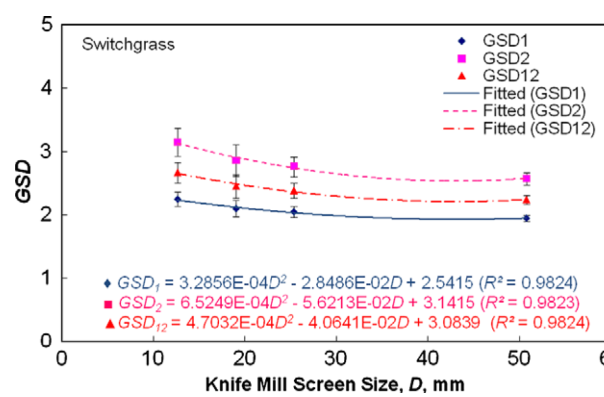

Fig. 7. Variation in geometric standard deviation (GSD) of particle size distribution with knife mill screen size for switchgrass chopped samples (error bars represent standard deviation from the mean).

Table 5
Significant interactions of parameters on second order polynomial equations for knife mill size reduction of switchgrass.

Parameter	Mean sum square								
	D	F	N	$D·F$	$F·N$	$N·D$	D^2	F^2	N^2
X_{gm}	480.43[a]	4.560[a]	3.341[a]	5.308[a]	0.937[a]	1.528[a]	60.23[a]	1.547[a]	0.081
S_{gm}	0.001	0.020[a]	0.001	0.020	0.017	4E-06	0.172	0.005	0.003
a	948.40[a]	8.653[a]	7.902[a]	14.482[a]	0.851	3.207[a]	145.864[a]	2.328[a]	0.188
b	0.232[a]	0.011[a]	0.009[a]	0.004[a]	0.014[a]	0.001	0.033[a]	0.013[a]	0.013[a]
D_{50}	597.215[a]	4.355[a]	5.139[a]	7.989[a]	0.937	1.875	85.832[a]	1.888[a]	0.039
D_{10}	53.75[a]	0.096	0.485[a]	0.319[a]	0.355[a]	0.121	5.548[a]	0.390	0.015
RS_m	0.845[a]	0.034[a]	0.051[a]	0.028[a]	0.043[a]	0.007	0.166[a]	0.049[a]	0.048
I_u	35.60[a]	1.847[a]	1.118[a]	0.427	2.172[a]	0.152	4.442[a]	1.961[a]	1.967
N_{sg}	5973125[a]	43270[a]	51374[a]	79975[a]	9444	18682	857912[a]	18906[a]	388
C_u	8.836[a]	0.327[a]	0.637[a]	0.352[a]	0.426[a]	0.092	1.972[a]	0.526[a]	0.500[a]
C_g	0.008[a]	3E-04[a]	5E-04[a]	2E-04[a]	4E-04[a]	1E-04	0.002[a]	5E-04[a]	5E-04[a]
GSD_1	0.294[a]	0.012[a]	0.018[a]	0.010[a]	0.015[a]	0.003	0.059[a]	0.017[a]	0.017[a]
GSD_2	1.099[a]	0.043[a]	0.072[a]	0.039[a]	0.055[a]	0.010	0.228[a]	0.064[a]	0.062[a]
GSD_{12}	0.586[a]	0.023[a]	0.037[a]	0.020[a]	0.029[a]	0.005	0.119[a]	0.034[a]	0.033[a]

[a] Parameter coefficients significant at 95% confidence level.

Table 6
Parameter coefficients of second order polynomial equations for knife mill size reduction of switchgrass.

Parameter	Constant	D	F	N	$D·F$	$F·N$	$N·D$	D^2	F^2	N^2	R^2
X_{gm}	−4.560	0.979	−1.074	−3.610E-3	−6.217E-3	1.408E-3	−2.195E-4	−8.785E-3	4.624E-2	–	0.882
S_{gm}	2.694	–	−9.326	–	–	–	–	–	–	–	0.027
a	−10.205	1.403	−0.690	3.592E-2	−4.575E-3	–	2.020E-4	1.377E-2	5.574E-2	–	0.886
b	0.847	2.172E−2	−5.210E-2	1.555E-3	−1.033E-2	8.447E-5	–	−1.603E-4	4.783E-3	−2.726E-6	0.514
D_{50}	−6.432	1.026	−0.541	−1.342E-3	−5.834E-3	–	–	−1.045E-2	4.968E-2	–	0.884
D_{10}	−2.190	0.267	–	−6.956E-4	−6.757E-4	4.043E-5	–	−2.640E-3	–	–	0.856
RS_m	3.248	−4.761	9.413E-2	−2.913E-3	2.123E-3	−1.517E-4	–	3.780E-4	−9.285E-3	–	0.504
I_u	0.185	0.234	−0.314	1.533E-2	–	1.035E-3	–	−2.628E-3	−2.845E-5	–	0.488
N_{sg}	−643.40	102.55	−54.047	−0.134	−0.586	–	–	−1.045	4.972	–	0.884
C_u	8.515	−0.162	0.301	−9.305E-3	7.043E-3	−4.792E-4	–	1.331E-3	−3.038E-2	1.645E-5	0.497
C_g	1.330	−4.620E-3	9.374E-3	−2.893E-4	2.084E-4	−1.520E-5	–	3.641E-5	−9.151E-4	5.090E-7	0.506
GSD_1	2.685	−2.829E-2	5.535E-2	−1.718E-3	1.258E-3	−8.920E-5	–	2.264E-4	−5.485E-3	3.024E-6	0.503
GSD_2	4.009	−5.552E-2	0.107	−3.307E-3	2.449E-3	−1.712E-4	–	4.483E-4	−1.063E-2	5.829E-6	0.501
GSD_{12}	3.283	−4.024E-2	7.796E-2	−2.419E-3	1.782E-3	−1.255E-4	–	3.236E-4	−7.751E-3	4.262E-6	0.502

– Represents non-significant coefficient dropped from equation.

switchgrass distribution curves without deviation. Parameters RS_m, C_u, C_g, and GSD were the measure of breadth of distribution and parameters b and I_u measured height of distribution.

3.3. Regression analysis

All size-related parameters (X_{gm}, a, D_{50}, D_{10}, and N_{sg}) depended strongly on screen size, D, and moderately on mass feed rate, F, and speed, N ($P < 0.05$) (Table 5). Insignificant independent variables and their interactions of second order polynomial equations were verified for $P < 0.05$ and discarded (Table 6). Size-related parameters X_{gm}, a, D_{50}, D_{10}, and N_{sg} had R^2 values of 0.882, 0.886, 0.884, 0.856, and 0.884, respectively, for second order polynomial equations as functions of knife mill operating factors. Distribution-related parameters (S_{gm}, b, RS_m, I_u, C_u, C_g, and GSD) were predicted with moderate R^2 value. Switchgrass chop of specific particle size and distribution statistics can now be produced by calculating the knife mill operating factors from polynomial equations (Table 6). Particle size- and distribution-critical applications could utilize these equations and prepare switchgrass chop with control over knife mill speed, mass flow rate, and screen size.

4. Conclusions

Knife mill screen size was the controlling factor to determine particle size of switchgrass chop, but other operating factors such as feed rate and speed had moderate effect. Rosin–Rammler equation fitted size distribution data of chopped switchgrass with $R^2 > 0.982$. Rosin–Rammler size parameter was always greater than median length, which was greater than geometric mean length. Rosin–Rammler distribution parameter was inversely proportional to mass relative span. Mass relative span was greater than 1, which indicated wide distribution of particle sizes. Uniformity coefficient was >4.0, which indicated a wide assortment of particles and also represented a well-graded particle size distribution. Knife mill chopping of switchgrass resulted in ‘strongly fine skewed mesokurtic’ particles for 12.7–25.4 mm screens and ‘fine skewed mesokurtic’ particles for 50.8 mm screen. Distribution geometric standard deviation had improved relation with screen size compared to geometric standard deviation. Size-related parameters (geometric mean length, X_{gm}, Rosin–Rammler size parameter, a, median size, D_{50}, effective size, D_{10}, and size guide number, N_{sg}) were fit as a function of knife mill screen size, D, feed rate, F, and mill speed, N. Analysis of particles will lead to the selection of knife mill operating parameters to produce a particular chop.

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