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Direct mechanical energy measures of hammer mill comminution of switchgrass, wheat straw, and corn stover and analysis of their particle size distributions

Venkata S.P. Bitra [a], Alvin R. Womac [a,*], Nehru Chevanan [a], Petre I. Miu [a], C. Igathinathane [b], Shahab Sokhansanj [c], David R. Smith [a]

[a] Department of Biosystems Engineering and Soil Science, 2506 E.J. Chapman Drive, The University of Tennessee, Knoxville, Tennessee 37996, USA
[b] Agricultural and Biological Engineering Department, 130 Creelman Street, Mississippi State University, Mississippi State, Mississippi 39762, USA
[c] Oak Ridge National Laboratory, Environmental Sciences Division, Oak Ridge, P.O. Box 2008, Tennessee, 37831, USA

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ABSTRACT

Biomass particle size impacts handling, storage, conversion, and dust control systems. Size reduction mechanical energy was directly measured for switchgrass (*Panicum virgatum* L.), wheat straw (*Triticum aestivum* L.), and corn stover (*Zea mays* L.) in an instrumented hammer mill. Direct energy inputs were determined for hammer mill operating speeds from 2000 to 3600 rpm for 3.2 mm integral classifying screen and mass input rate of 2.5 kg/min with 90°- and 30°-hammers. Overall accuracy of specific energy measurement was calculated as ±0.072 MJ/Mg. Particle size distributions created by hammer mill were determined for mill operating factors using ISO sieve sizes from 4.75 to 0.02 mm in conjunction with Ro-Tap® sieve analyzer. A wide range of analytical descriptors were examined to mathematically represent the range of particle sizes in the distributions. Total specific energy (MJ/Mg) was defined as size reduction energy to operate the hammer mill plus that imparted to biomass. Effective specific energy was defined as energy imparted to biomass. Total specific energy for switchgrass, wheat straw, and corn stover grinding increased by 37, 30, and 45% from 114.4, 125.1, and 103.7 MJ/Mg, respectively, with an increase in hammer mill speed from 2000 to 3600 rpm for 90°-hammers. Corresponding total specific energy per unit size reduction was 14.9, 19.7, and 13.5 MJ/Mg mm, respectively. Effective specific energy of 90°-hammers decreased marginally for switchgrass and considerably for wheat straw and it increased for corn stover with an increase in speed from 2000 to 3600 rpm. However, effective specific energy increased with speed to a certain extent and then decreased for 30°-hammers. Rosin–Rammler equation fitted the size distribution data with $R^2 > 0.995$. Mass relative span was greater than 1, which indicated a wide distribution of particle sizes. Hammer milling of switchgrass, wheat straw, and corn stover with 3.2 mm screen resulted in 'well-graded fine-skewed mesokurtic' particles. Uniformity coefficient was <4.0 for wheat straw, which indicated uniform mix of particles, and it was about 4.0 for switchgrass and corn stover, which indicated a moderate assortment of particles. Size-related parameters, namely, geometric mean diameter, Rosin–Rammler size parameter, median diameter, and effective size had strong correlation among themselves and good negative correlation with speed. Distribution-related parameters, namely, Rosin–Rammler distribution parameter, mass relative span, inclusive graphic skewness, graphic kurtosis, uniformity index, uniformity coefficient, coefficient of gradation and distribution geometric standard deviation had strong correlation among themselves and a weak correlation with mill speed. Results of this extensive analysis of specific energy and particle sizes can be applied to selection of hammer mill operating factors to produce a particular size of switchgrass, wheat straw, and corn stover grind, and will serve as a guide for relations among the energy and 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 [1] apart from wheat straw and corn stover. For efficient conversion of biomass to bioenergy, an optimized supply chain ensures timely supply of biomass with minimum costs [2]. Conversion of naturally occurring lignocellulosic materials to ethanol currently requires preprocessing to enhance the accessibility of reactive agents and to improve conversion rates and yields. According to one patent, agricultural biomass was prepared to approximately 1 to 6 mm by a disc refiner for ethanol production [3].

* Corresponding author. Tel.: +1 865 974 7104; fax: +1 865 974 4514.
E-mail address: awomac@utk.edu (A.R. Womac).

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Such reduced particle sizes can be achieved by fine grinders (e.g. hammer mill, disc refiner, pin mill, chain mill). Long pieces of straw/stalk of biomass may not flow easily into grinders such as hammer and disc refiners. Hence, biomass needs to be chopped with a knife mill to accommodate bulk flow, densification, and uniformity of feed rate. 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 [4]. Higher surface area increases number of contact points for chemical reactions [5], which may require grinding to a nominal particle size of about 1 mm [6]. Size reduction alone can account for one-third of the power requirements of the entire bioconversion to ethanol [6,7] and warrants improvement to raise the energy efficiency of biofuels. 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 renewable energy research trend is driven by the need to reduce the cost of biomass ethanol production. Preprocessing research is focused on developing processes that would result in reduced bioconversion time, reduced enzyme usage and/or increased ethanol yields [8]. 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, wheat straw, and corn stover.

Energy demand for grinding depends on its initial particle size, moisture content, material properties, mass feed rate, and machine variables [9]. Performance of a grinding device is often measured in terms of energy requirement, geometric mean diameter, and resulting particle size distribution. Although not always explicitly stated, most studies reported total specific energy. Mani et al. [9,10] observed that energy requirement increased rapidly with decreasing particle size. They found that switchgrass required the highest effective specific energy (99 MJ/Mg) to grind using a laboratory hammer mill, whereas corn stover required less effective specific energy (40 MJ/Mg) for 3.2 mm screen using the same grinder. They indirectly estimated mechanical energy using a wattmeter to monitor an electric motor. In another study, about 6.2 to 12.5% of the total energy content of hardwood chips was required as total specific energy to grind the chips to 50 to 100 mesh size [11].

Hammer mills have achieved merit because of their ability to finely grind a greater variety of materials than any other machine [12]. Himmel et al. [13] observed that total specific energy for size reduction of wheat straw using 1.6 mm hammer mill screen was twice that for a 3.2 mm screen. They used an indirect method of measuring electric power with a wattmeter and corrected with power factors, though motor efficiency was unaccounted. Austin and Klimpel [14] noted that strain energy stored in the material before breaking was converted to energy, other than new surface development energy, such as propagated stress wave energy, kinetic energy of fragments, and plastic deformation energy. Fraction of total energy converted to surface energy will be extremely variable, depending on the operating conditions of mill. It should be noted that the theoretical analyses of size reduction primarily pertains to brittle failure of homogeneous materials, which is not representative of lignocellulosic biomass.

Past research was carried out with an aim to measure indirect energy. Balk [15] used a wattmeter to relate hammer mill total specific energy with moisture content and feed rate of coastal bermudagrass. Moisture content and grind size influenced the specific energy. Datta [11] reported that size reduction of hardwood chips to 0.2–0.6 mm required 72–144 MJ/Mg, whereas size reduction of particles to 0.15–0.3 mm required five times more total specific energy (360–720 MJ/Mg). Arthur et al. [16] found that total specific energy requirement of a tub grinder decreased from 2696 to 1181 MJ/Mg with an increase in screen size from 12.7 to 50.8 mm for rectangular wheat straw bales. They reported wheat straw grinding rate increased from 0.137 to 0.267 Mg/min with an increase in screen size from 12.7 to 50.8 mm. Also, they found that grinding rate increased with an increased tub rotational speed from 3.1 to 9.5 rpm. However, the rate of increase of grinding rate became less as the tub speed increased. Their indirect measurement of total specific energy was based on engine fuel consumption rate and did not take into account energy conversion by an internal combustion engine. Total specific energy to chop green wood was 288 MJ/Mg for a hammer mill at 2500 rpm based on a wattmeter [5]. Samson et al. [17] reported that total specific electric energy requirement of switchgrass hammer milling with 5.6 mm screen was 162 MJ/Mg. Jannasch et al. [18] reported wattmeter-measured total specific energy of 201 MJ/Mg for both 5.6 and 2.8 mm screens for hammer mill grinding of switchgrass. Esteban and Carrasco [19] estimated total specific energy requirements of 307, 427, and 71 MJ/Mg for poplar chips, pine chips, and pine bark, respectively, in a hammer mill (1.5 mm screen) using ampere meter and vacuum discharge. Thus, most of the published energy values were based on indirect measures of total specific energy.

Cadoche and López [20] tested knife and hammer mills on hardwood chips, agricultural straw and corn stover. Effective specific energy demand to reduce hardwood chips to a particle size of 1.6 mm was 468 MJ/Mg for both hammer and knife mills. Hammer mill required more energy (414 MJ/Mg) than a knife mill (180 MJ/Mg) for 3.2 mm particle size. They observed that agricultural straw and corn stover required 6 to 36% of the effective specific energy required for wood. Vigneault et al. [21] observed a 13.6% saving in total specific energy requirement and an increase of 11.1% in grinding rate by using thin hammers (3.2 mm) instead of thick hammers (6.4 mm) without affecting geometric mean diameter and geometric standard deviation of corn grind. They indirectly measured total specific energy using a wattmeter. Total specific energy of hammer mill grinding of corn increased from 17 to 46 MJ/Mg for an increase in hammer tip speed from 54 to 86 m/s for 6.4 mm-thick hammer [22]. High speed hammer mills with smaller diameter rotors are good for fine or hard to grind material. However, at high tip speeds, material moves around the mill parallel to the screen surface making the openings only partially effective. At slower speeds, material impinges on the screen at a greater angle causing greater amounts of coarser feed to pass through [23]. Operating speeds of hammer mill seem to be critical to find appropriate effective specific energy demand for biomass size reduction.

Nominal biomass particle sizes produced by hammer mill grinding depend on operating factors of the mill. Himmel et al. [13] observed ground wheat straw retention on 60 mesh screen decreased when hammer mill screen size decreased from 3.2 to 1.6 mm, which indicated skewing of particle size distribution curve to finer sizes. They observed a shift in the distribution curve toward large sizes of aspen wood when negative pressure was applied to the collection side of mill screen. Negative pressure of 25 mm water increased wheat straw feed rate by 50% (from 1.67 to 2.50 kg/min) for 3.2 mm screen and no-effect on feed rate of aspen wood chips without significant increase in power demand of knife mill [13].

Yang et al. [24] fitted the particle size distribution data of alfalfa forage grinds from a hammer mill with a log-normal distribution equation. They found that median size and standard deviation were 238 μm and 166 μm, respectively. Mani et al. [9] determined sieve-based particle size distribution of hammer milled wheat and barley straws, corn stover, and switchgrass. Particle size distribution of corn stover grind from various hammer mill screens depicted positive skewness in distribution [25]. In actual practice, measured geometric mean diameter of biomass particles using sieve analysis is less than the actual size of the particles. Womac et al. [26] 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 [27]. 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 [28] 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 [29,30]. Also, particle size distributions of alginate-pectin microspheres were well fit with the Rosin–Rammler model [31].

Little published data on hammer mill total and effective specific energy requirement and particle size distribution due to various operating factors is available for switchgrass, wheat straw, and corn stover. Also, size reduction studies on hammer mill equipped with direct measurement of mechanical input energy are scarce in the literature. Hence, the first objective of this research was to determine the direct mechanical input energy for hammer mill size reduction of switchgrass, wheat straw, and corn stover over a range of operating speeds with 90°- and 30°-hammers. The second was to evaluate corresponding Rosin–Rammler particle size distribution function and other analytic descriptors for the description of sieve-based particle distributions.

2. Materials and methods

2.1. Biomass test material

Switchgrass (*Panicum virgatum* L.), wheat straw (*Triticum aestivum* L.), and corn stover (*Zea mays* L.) were size reduced in a knife mill as a preparation for hammer milling. Switchgrass and wheat straw were manually removed from bales (1.00 × 0.45 × 0.35 m) for sample mass determinations. Corn stover was cut into about 150 mm long pieces with arborist pruners. Samples were initially chopped in knife mill with 25.4 mm screen using optimum speed of 250 rpm and optimum feed rates of 7.6, 5.8, and 4.5 kg/min for switchgrass, wheat straw, and corn stover, respectively. The representative geometric mean length of switchgrass, wheat straw, and corn stover particles were 8.3, 7.1, and 8.3 mm, respectively, determined by ASABE sieves [26].

Moisture contents of switchgrass, wheat straw, and corn stover were determined as 9.0 ± 0.5% wet basis following American Society of Agricultural and Biological Engineers (ASABE) Standards for forages by oven drying the samples at 103 ± 2 °C for 24 h [32]. Switchgrass and wheat straw had been harvested as hay, allowed to dry in a swath prior to baling and then bales were stored indoors for three months. Corn stover was also allowed to field dry after ear harvest and the stover was stored in indoors for three months before experiments.

2.2. Hammer mill and operating variables

A hammer mill (Schuttle Buffalo, Buffalo, NY) with a 230 mm diameter rotor powered with a gasoline engine rated at 18 kW (Fig. 1) was used for grinding. The hammer mill rotor had sixteen swinging hammers in four sets pinned to its periphery. Length and thickness of each hammer were 178 and 6.4 mm, respectively. The performance of dull versus sharp hammers of same hammer thickness was investigated to explore whether any advantage could be realized by knife shear action, or whether the relative high velocity of impact dominated in the failure of fibrous biomass. Hammer thickness of dull and sharp hammers were same to no introduce the variable hammer thickness into experiments. Previously, thin hammers performed better than thick hammers [21]. Hammers tested included 90° (dull) and 30° (sharp) leading edges. An interchangeable classifying screen of 3.2 mm was mounted around the rotor. Hammer clearance with screen was 5 mm. An engine rated speed of 3600 rpm powered the hammer mill at the same speed by using a V-groove pulley and belt drive system. Various engine throttle settings operated the hammer mill at speeds ranging from 2000 to 3600 rpm (5 levels) to examine speed effects. Corresponding tip speeds were 48 to 87 m/s, respectively. These speeds were within the range of commercial milling of agricultural products using hammer mills [19,21,22]. Hammer mill bottom was connected to a dust collector maintaining a negative suction pressure of 60 mm of water to overcome air-flow resistance of 3.2 mm screen and biomass, to reduce dust losses, and to improve flow of input feed.

2.3. Mass feed control to hammer mill

Weighed switchgrass, wheat straw and corn stover samples (±50 g accuracy) were distributed on a 6.1 m long inclined belt conveyor. Belt speed was adjusted to feed the sample into hammer mill in 75 s. This arrangement provided a means to consistently feed the test material into hammer mill at a 2.5 kg/min mass feed rate. Same feed rate was maintained in all the studies. Increased feed rates decreased the total specific energy [16]. Hence, the maximum possible feed rate of 2.5 kg/min was determined in pre-tests corresponding to 3.2 mm classifying screen opening size and 2000 rpm under suction pressure. This feed rate gave smooth flow of switchgrass, wheat straw, and corn stover through hammer mill for all rotor speeds tested.

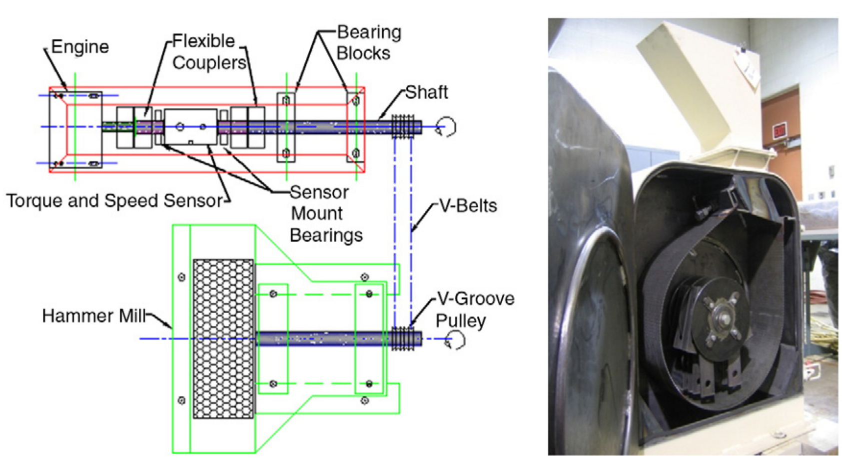

Fig. 1. Overhead view of hammer mill and instrumentation set up and picture showing hammers and classifying screen of hammer mill.

2.4. Instrumentation and data acquisition

Mechanical power input into the hammer mill was directly monitored with a calibrated torque and speed sensor (±0.05% accuracy) (Series 4200 PCB Piezotronics, Depew, NY) in a driveshaft between the engine to the driver sheave using commercial S-flex shaft couplings (Fig. 1). Torque and speed data streams were collected during steady state operation for 60 s with an analog-to-digital signal processing module (National Instruments, Austin, TX) and laptop computer.

Torque and speed raw data were analyzed using LabView Version 8 Fast Fourier Transform data analysis module to determine power-frequency spectra for torque and speed. Sensor sampling frequency was determined by sampling each channel from 1 to 24 kHz, and then examining the frequency-based power spectra [33], and then applying Nyquist sampling theorem [34] to ensure sampling at least 2× the highest frequency that had appreciable power. Engineering-unit converted data were filtered using a 2nd-order Butterworth band-pass filter. Low cutoff frequency of filter was 1 Hz and high cutoff frequencies used were 499, 1999, 3999, 5999, 7999, 9999, and 11998 Hz for data sampling rates of 1, 4, 8, 12, 16, 20, and 24 kHz, respectively. Most of the torque and speed frequencies were in the order of 20 and 2 Hz, respectively, for all power spectra between 1 and 24 kHz sampling rates during no-load run (Fig. 2 depicts 1 and 4 kHz samplings) and 20 and 4 Hz for switchgrass grinding (Fig. 3 for 2400 rpm). A sampling rate of 1 kHz was determined. In addition to continuous computer monitoring of a speed sensor, independent measures of hammer mill speeds were taken with a handheld laser tachometer (±0.05% accuracy). Overall accuracy of total and effective specific energy determinations was calculated to be ±0.072 MJ/Mg.

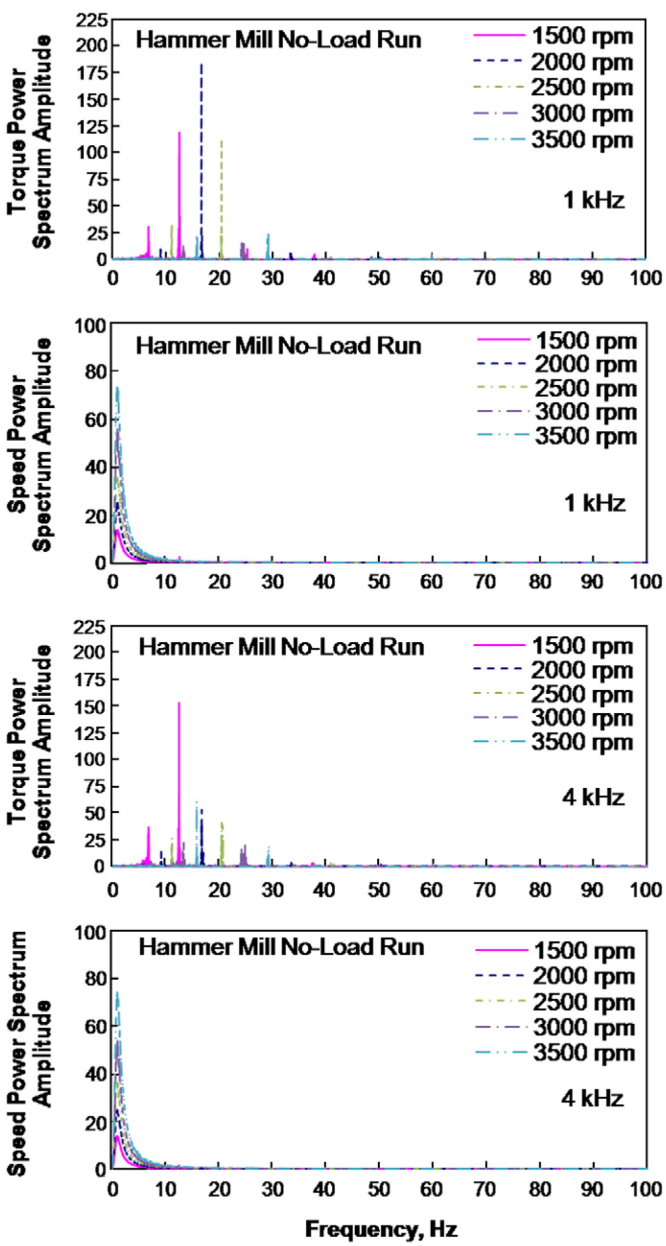

Fig. 2. Power spectra of torque and speed for 1 kHz and 4 kHz data acquisition sampling rates during no-load run of hammer mill.

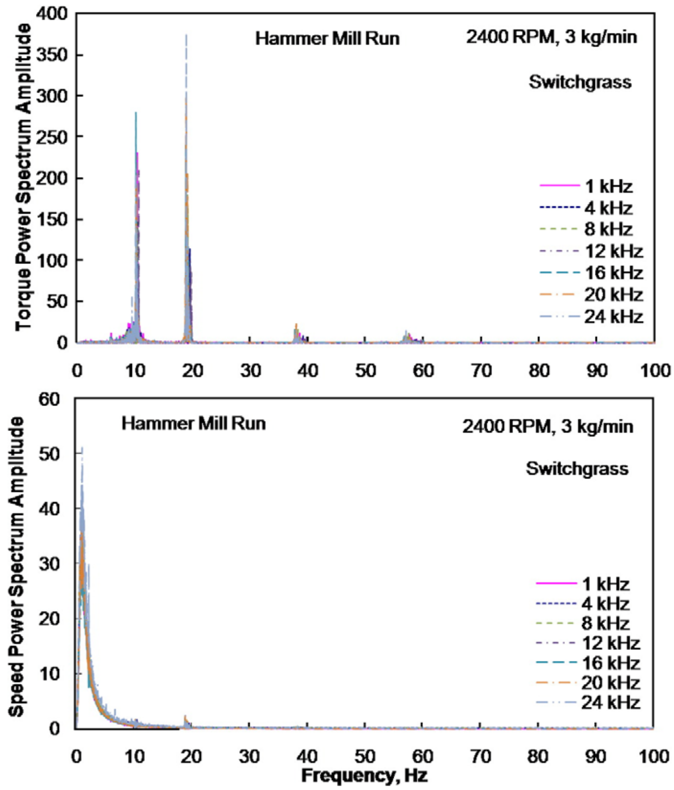

Fig. 3. Power spectra of torque and speed for various data acquisition sampling rates during switchgrass milling of hammer mill.

2.5. Test procedure and sample collection

Initially, hammer mill no-load run power demand at different speeds from 1500 to 3500 rpm was determined at different sampling frequencies from 1 to 24 kHz. No-load power data were fitted as a function of speed.

Test samples were weighed using a digital crane scale (±0.1 kg). While hammer mill was running, the conveyor dropped a continuous stream of test sample into hammer mill hopper. Ground samples were collected in a cloth bag of dust collector. 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 Ro-Tap® sieve analyzer (W.S. Tyler, Mentor, OH). Each experimental unit had three replicate measures.

2.6. Sieve analysis

Each switchgrass, wheat straw, and corn stover sample after size reduction was analyzed for particle size distribution analysis using ASABE standard S319.3 [35]. A Ro-Tap® sieve analyzer used nineteen ISO sieves (4.750, 3.350, 2.360, 1.700, 1.180, 0.850, 0.600, 0.425, 0.300, 0.212, 0.150, 0.160, 0.075, 0.053, 0.045, 0.038, 0.032, 0.025, and 0.020 mm

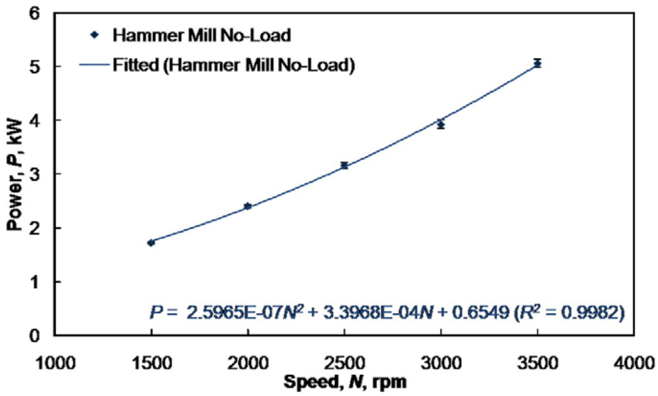

Fig. 4. No-load power demand of hammer mill with speed.

nominal sieve opening sizes). The first thirteen sieves (4.750–0.075 mm) initially partitioned samples. Material collected in the dust pan was subsequently transferred to the last six sieves (0.053–0.020 mm) for successive sieving. Particles from each sieve and pan were collected and weighed using an electronic top pan balance (±0.01 g accuracy). Each time, the sieve was operated for 10 min.

2.7. Data analysis

Total specific energy was determined by integrating power (torque and speed) over time, divided by the mass feed rate. No-load power function was subtracted from total power to estimate effective power for effective specific energy estimation [13,20,36].

Log-normal distribution plots between percent retained mass and geometric mean diameter of particles on each sieve, $\overline{X}_i$, were plotted on semi-log graph. Geometric mean diameter, X_{gm}, and geometric standard deviation, S_{gm}, were calculated based on mass fraction [35]. Total specific energy per unit size reduction was calculated by dividing total specific energy with the difference in geometric mean diameter caused by size reduction. Similarly, effective specific energy per unit size reduction was also calculated.

Percent cumulative undersize mass as a function of nominal sieve aperture size was graphed on semi-log plot. Curves were characterized as well-graded, gap (step)-graded, or poorly-graded [38,39]. Cumulative undersize mass percentage data obtained through Ro-tap sieve analysis was regressed using Rosin–Rammler distribution equation [28]. This equation was selected based on previous success with sieved materials [29–31,40]. Rosin–Rammler equation is as follows:

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

where, M_{cu} is cumulative undersize mass, %; D_p is particle size, assumed equivalent to nominal sieve aperture size, mm; a is size parameter, or Rosin–Rammler geometric mean diameter, mm; and, b is distribution parameter, or Rosin–Rammler skewness parameter (dimensionless). From Eq. (1), particle sizes in mm corresponding to 10, 50, and 90% cumulative undersize mass (D_{10}, D_{50} (median diameter), and D_{90}, respectively) were evaluated to calculate mass relative span as an indicator of distribution width. It should be noted that median diameter is different from geometric mean diameter for skewed distribution [37]. The size D_{10} is also known as effective size [39]. Mass relative span, RS_m, provides a dimensionless measure of particle size distribution width [41] and was determined as follows:

$$RS_m = (D_{90} - D_{10}) / D_{50} \quad (2)$$

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 and graphic kurtosis were calculated [42].

Generally, uniformity index and size guide number of particle size distribution are determined using the procedure of Canadian Fertilizer Institute [43]. 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 [43]. These calculations are prone to positive and negative errors due to linear interpolation [29]. Due to this limitation, in the present study, uniformity index was assessed as stated by Perfect and Xu [29] from Eq. (1). Median diameter multiplied by 100 gave size guide number. Coefficient of uniformity and coefficient of gradation of particle size distribution were evaluated [39]. 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}) were determined [37].

SAS ANOVA procedure [44] was used for mean separation. Pearson correlation coefficients were determined using SAS PROC CORR procedure [44] among hammer type, mill speed, total and effective specific energy, geometric mean diameter, geometric standard deviation, Rosin–Rammler parameters, median diameter, effective size, mass relative span, inclusive graphic skewness, graphic kurtosis, uniformity index, uniformity coefficient, and distribution geometric standard deviation.

3. Results and discussion

3.1. Hammer mill no-load power requirement

No-load power requirement of hammer mill increased curvilinear by 66% from 1.72 ± 0.02 kW at 1500 rpm to 5.06 ± 0.07 kW at 3500 rpm (Fig. 4). Increased power was attributed to increasing speed

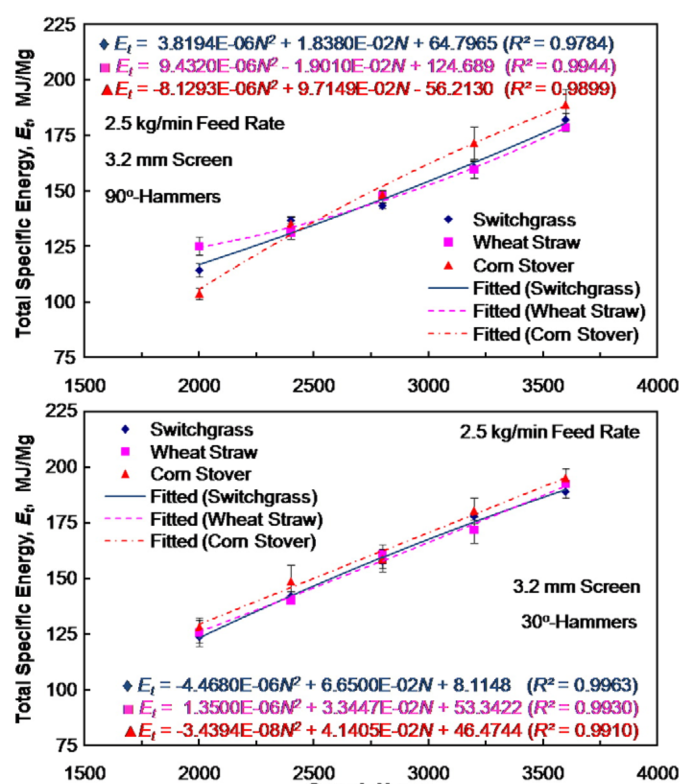

Fig. 5. Total specific energy of switchgrass, wheat straw, and corn stover with hammer mill speed for 90°- and 30°-hammers.

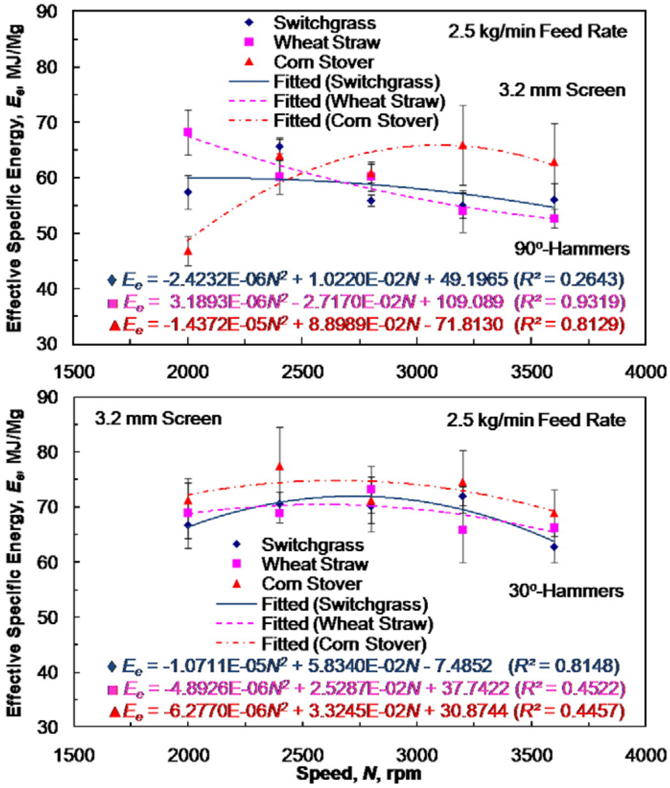

Fig. 6. Effective specific energy of switchgrass, wheat straw, and corn stover with hammer mill speed for 90°- and 30°-hammers.

at essentially marginal increase in torque (10.89 to 13.86 N m). Large hammer mill bearings contributed to torque resistance.

3.2. Effect of speed on total and effective specific energy

Average total specific energy, E_t, of switchgrass, wheat straw, and corn stover increased by 37, 30, and 45%, respectively, with an increase in hammer mill speed from 2000 to 3600 rpm for 90°-hammers (Fig. 5). Increased speeds allowed the particles to move freely around the mill parallel to the classifying screen surface [23]. Free movement of particles along the screen at higher speeds also contributed for increased total specific energy apart from energy demand for moving the mill rotor. Total specific energy for switchgrass, wheat straw, and corn stover were 114.4, 125.1, and 103.7 MJ/Mg at 2000 rpm. Total specific energy values were less than the values reported for switchgrass [17,18]. Brittle material like coal needed 18 to 24 MJ/Mg of energy to produce 100 to 200 mesh size with hammer mill [11]. Hence, present lignocellulosic fibrous biomasses required higher energy compared to brittle material, as the fracture mechanism was different. In case of 30°-hammers, total specific energy of switchgrass, wheat straw, and corn stover increased by 34, 34, and 34% from 123.6, 125.8, and 128.2 MJ/Mg, respectively (Fig. 5). Therefore, there was a significant increase (95% confidence level) in total energy while grinding with 30°-hammers compared to 90°-hammers. Thus, it appears that shear failure at high speed impact of fibrous materials offered no advantage in energy utilization. More contact hitting area of 90°-hammers was the influencing factor for reduced total specific energy. It was observed that there was no pronounced influence of input material type (all cellulosic fibrous materials) while grinding with hammer mill at speeds from 2000 to 3600 rpm for both the hammer types. Schell and Harwood [5] observed equal total specific energy for both bars and knives of hammer mill during poplar wood chips size reduction. In actual practice, the tip portion of hammers was coming in contact with material to impart an impact force on material. Also, a reduced mill speed evidently delivered enough impact failure because of corresponding reduced total specific energy for size reduction. This was primarily due to the inherent increase in no-load energy of the mill that is also influential of with-load energy. Hence, optimized total specific energies for switchgrass, wheat straw, and corn stover were obtained at 2000 rpm for mass feed rate of 2.5 kg/min and 3.2 mm screen. Lower speeds than 2000 rpm were not possible to run the mill with load-condition using 2.5 kg/min feed rate.

Average effective specific energy, E_e, of switchgrass and wheat straw decreased gradually by 2 and 23% from 57.5 and 68.2 MJ/Mg, respectively, for 90°-hammers with an increase in hammer mill speed from 2000 to 3600 rpm (Fig. 6). On the other hand, it increased by 26% from 46.8 MJ/Mg for corn stover. Mani et al. [9,10] also observed higher effective specific energy for switchgrass (99 MJ/Mg) than effective specific energy for corn stover (40 MJ/Mg). However, effective specific energy consumed for 30°-hammers increased with speed to a certain extent and then decreased. The overall marginal reduction of effective specific energy for 30°-hammers was 6, 4, and 3% from 66.7, 68.9, and 71.3 MJ/Mg for switchgrass, wheat straw, and corn stover, respectively, with an increase in speed from 2000 to 3600 rpm. Effective specific energy was significantly less (95% confidence interval) for 90°-hammers at all speeds compared to 30°-hammers.

3.3. Particle size analysis of hammer mill size reduction

3.3.1. Size distribution

Mass percent retained on each test sieve, M, in relation to geometric mean diameter of particles on each sieve showed log-normal distribution for all hammer mill speeds of 90°- and 30°-hammers with switchgrass (Fig. 7), wheat straw (Fig. 8), and corn stover (Fig. 9) with certain skewness. But, all the distribution curves showed positive skewness or fine skewed for all speeds, which means increased fines in the material. About 70% of switchgrass, wheat straw, and corn

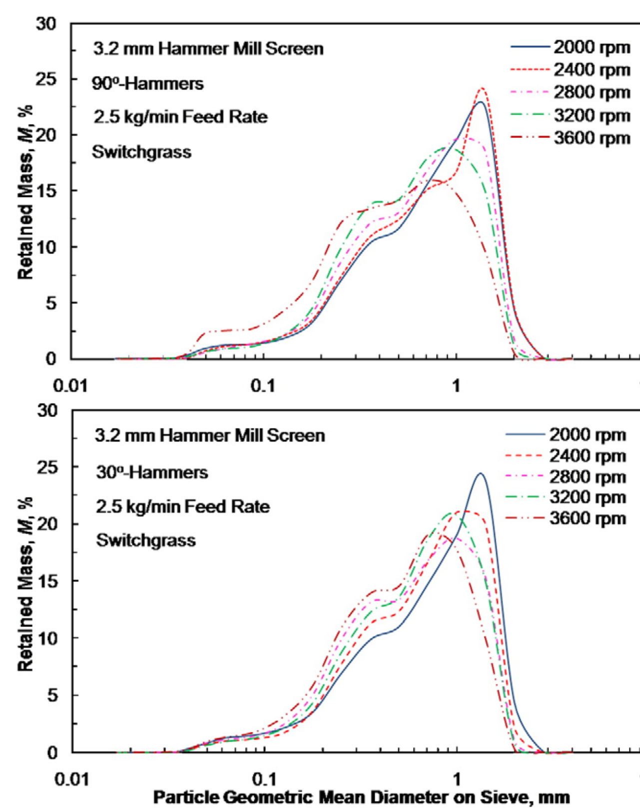

Fig. 7. Log-normal distribution of switchgrass hammer mill grind with 90°- and 30°-hammers.

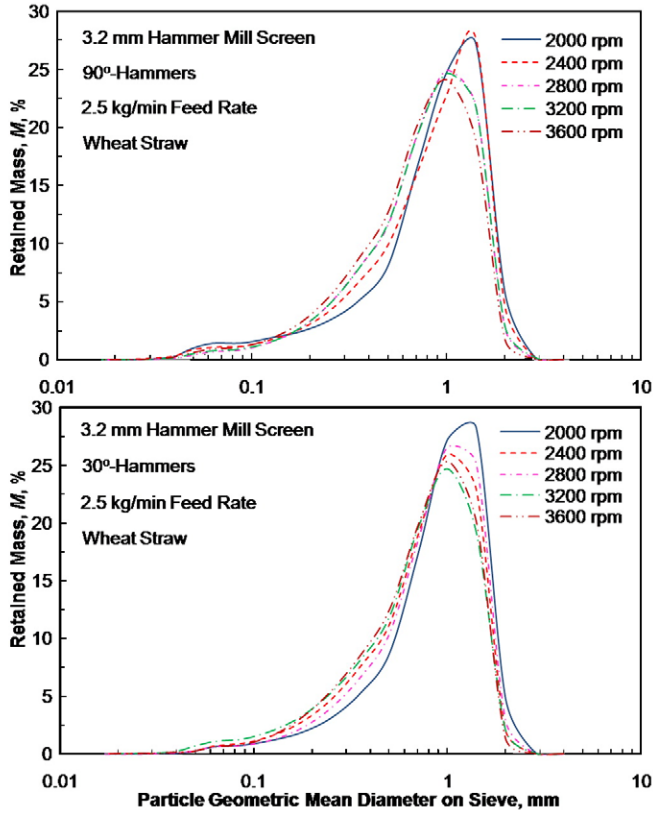

Fig. 8. Log-normal distribution of wheat straw hammer mill grind with 90°- and 30°-hammers.

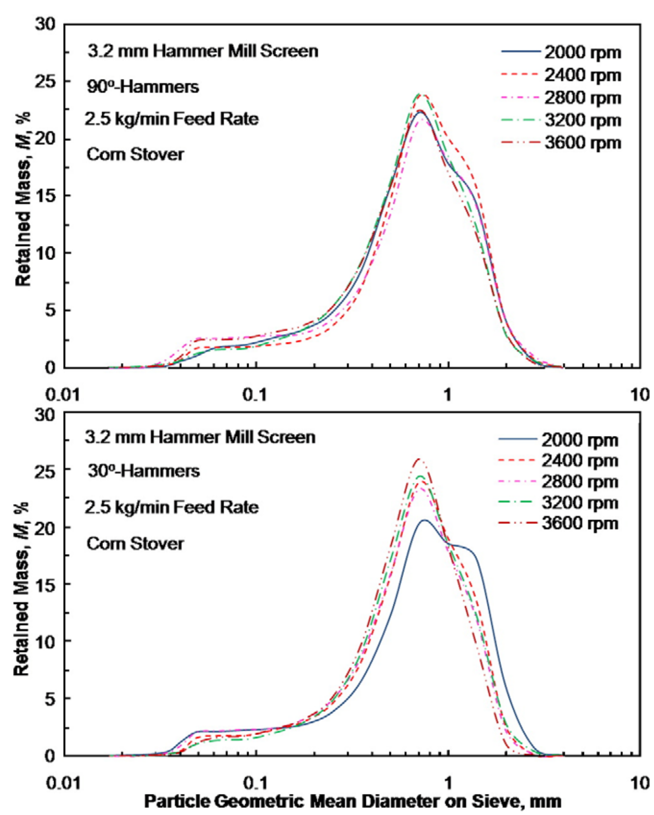

Fig. 9. Log-normal distribution of corn stover hammer mill grind with 90°- and 30°-hammers.

stover contained particle size <1 mm for all speeds, which indicated that a significant portion of these ground materials would support effective chemical reactions [5,6]. Different mean separations in particle size distribution curves were observed for five hammer mill speeds tested for 90°- and 30°-hammers. Increased speed increased amount of small particles. Similar trends were published for hammer mill grinds of wheat, soybean meal, corn [45], alfalfa [24], wheat straw [9,13], corn stover [13], switchgrass, and barley straw [9].

3.3.2. Geometric mean diameter and geometric standard deviation

Average geometric mean diameter, X_{gm}, of switchgrass, wheat straw, and corn stover decreased with an increase in hammer mill speed from 2000 to 3600 rpm for 90°-hammers (Fig. 10). Particle sizes observed for 30°-hammers were similar to 90°-hammers for mill speeds from 2000 to 3600 rpm. Wheat straw particles were coarser than switchgrass and corn stover. These hammer milled particles are generally suitable for most biochemical conversion [5,6]. Bargen et al. [23] also stated that hammer mill yielded fine and coarse particles at high and low speeds, respectively, for wheat straw, corn residues, and grain sorghum.

Geometric mean diameter was directly proportional to Rosin–Rammler size parameter (Table 1), median diameter and effective size (Table 2), and size guide number (Table 3). Mean separation of

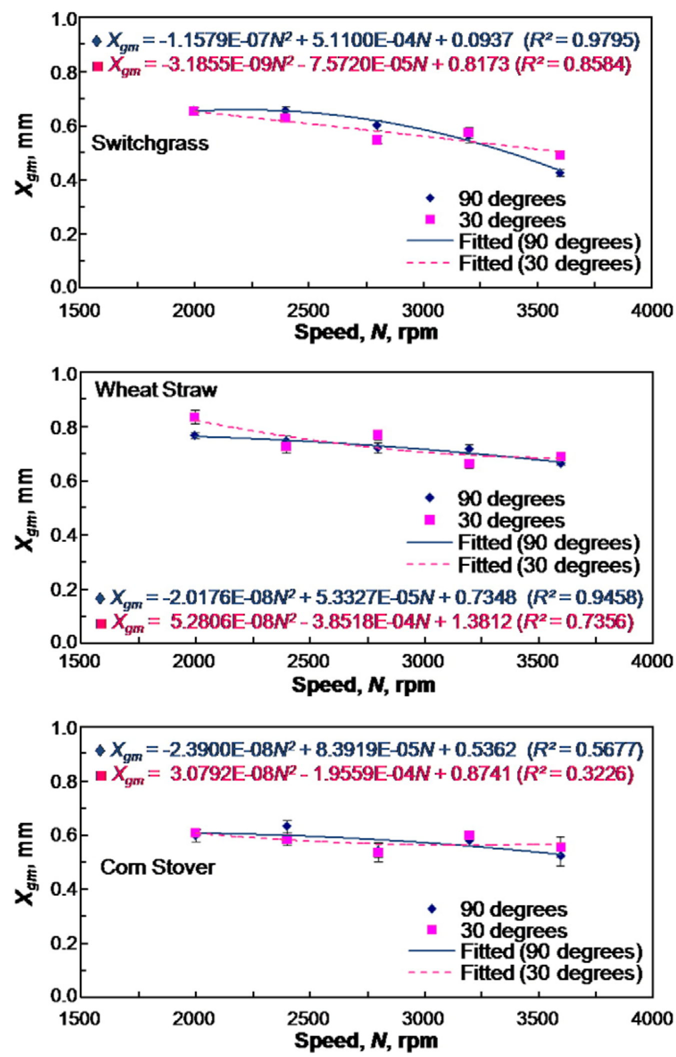

Fig. 10. Variation in geometric mean diameter of switchgrass, wheat straw, and corn stover hammer mill grind with speed for 90°- and 30°-hammers.

geometric mean diameter indicated significant difference ($p<0.05$) in particle sizes for 2800 and 3600 rpm among 90°- and 30°-hammers (Table 1). Minimum significant difference (MSD) test across geometric mean diameter resulted in similar groups between two hammer types tested. A negative strong correlation (−0.914, −0.815, and −0.615 for switchgrass, wheat straw, and corn stover, respectively) was established between geometric mean diameter, X_{gm}, and hammer mill speed, N (Table 4, data not presented for wheat straw and corn stover). Similar correlation was observed between geometric mean diameter and total specific energy. Hence, higher total specific energy yielded smaller particles.

Average geometric standard deviation, S_{gm}, did not maintain a specific trend with an increase in speed from 2000 to 3600 rpm which was due to unpredictable fracture characteristics of fibrous materials (Table 1). 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); standard deviation must always be greater than or equal to 1.0 [37] (Table 1). Standard deviation greater than 1.0 represented wide distribution of particles. Mean separation of geometric standard deviation indicated similar and coherent groups (Table 1). Geometric standard deviation, S_{gm}, could not establish any correlation with hammer mill operating factors and specific energy (Table 4).

Table 1
Estimated values of geometric mean diameter, geometric standard deviation, and parameters of Rosin–Rammler equation and its coefficient of determination for hammer mill size reduction of switchgrass, wheat straw, and corn stover with 90°- and 30°-hammers.

Hammer type	Mill speed, N, rpm	Geometric mean diameter, X_{gm}, mm*	Geometric standard deviation, S_{gm}*	Rosin–Rammler size parameter, a, mm*	Rosin–Rammler distribution parameter, b*	Coefficient of determination, R^2
Switchgrass						
90°	2000	0.65 a	2.25 bc	0.96 ab	1.57 abcd	0.999
	2400	0.65 a	2.22 bcd	0.96 ab	1.54 cd	0.999
	2800	0.60 bc	2.15 de	0.86 cd	1.59 abcd	0.999
	3200	0.56 cd	2.11 e	0.80 e	1.62 abc	0.999
	3600	0.43 f	2.41 a	0.64 g	1.36 e	0.999
30°	2000	0.65 a	2.29 b	0.97 a	1.53 d	0.998
	2400	0.63 ab	2.15 de	0.90 bc	1.63 ab	0.999
	2800	0.55 d	2.19 cde	0.79 e	1.54 cd	0.999
	3200	0.57 cd	2.11 e	0.82 de	1.65 a	0.999
	3600	0.49 e	2.17 cde	0.71 f	1.56 bcd	0.999
MSD		0.045	0.092	0.059	0.084	
Wheat straw						
90°	2000	0.76 b	2.23 a	1.10 a	1.85 bc	0.997
	2400	0.74 b	2.19 ab	1.07 ab	1.81 bc	0.998
	2800	0.72 bc	2.01 de	0.99 de	1.91 abc	0.999
	3200	0.71 bc	2.03 cde	0.99 de	1.88 abc	0.999
	3600	0.66 d	2.09 bcd	0.93 f	1.82 bc	0.999
30°	2000	0.83 a	1.93 e	1.12 a	2.20 a	0.999
	2400	0.72 bc	2.00 de	1.00 cd	1.95 abc	0.999
	2800	0.77 b	1.97 de	1.05 bc	2.06 ab	0.999
	3200	0.66 d	2.14 abc	0.95 ef	1.65 c	0.997
	3600	0.69 cd	2.00 de	0.96 def	1.62 c	0.995
MSD		0.052	0.125	0.049	0.349	
Corn stover						
90°	2000	0.60 abc	2.30 bc	0.87 bc	1.61 abc	0.999
	2400	0.63 a	2.32 bc	0.92 ab	1.70 ab	0.998
	2800	0.54 bc	2.69 a	0.87 bcd	1.37 c	0.996
	3200	0.58 abc	2.27 bc	0.84 cde	1.68 abc	0.999
	3600	0.53 c	2.48 ab	0.80 de	1.47 bc	0.998
30°	2000	0.61 ab	2.58 ab	0.95 a	1.46 bc	0.997
	2400	0.59 abc	2.27 bc	0.85 cd	1.70 ab	0.999
	2800	0.54 bc	2.41 abc	0.81 cde	1.56 abc	0.998
	3200	0.60 abc	2.15 c	0.84 cde	1.80 a	0.999
	3600	0.56 abc	2.13 c	0.78 e	1.84 a	0.999
MSD		0.080	0.323	0.070	0.320	

* 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.

Table 2
Median diameter, effective size, mass relative span, inclusive graphic skewness, and graphic kurtosis for hammer mill size reduction of switchgrass, wheat straw, and corn stover with 90°- and 30°-hammers.

Hammer type	Mill speed, N, rpm	Median diameter, D_{50}, mm*	Effective size, D_{10}, mm*	Mass relative span, RS_m*	Inclusive graphic skewness, GS_i*	Graphic kurtosis, K_g*
Switchgrass						
90°	2000	0.76 a	0.23 a	1.85 bcd	0.25 bcd	0.98 bcd
	2400	0.75 a	0.22 ab	1.89 bc	0.26 bc	0.98 bc
	2800	0.69 bc	0.21 abc	1.82 bcd	0.24 bcd	0.98 bcd
	3200	0.64 cd	0.20 bc	1.79 cd	0.24 cd	0.98 bcd
	3600	0.49 f	0.12 e	2.17 a	0.32 a	1.00 a
30°	2000	0.76 a	0.22 ab	1.90 b	0.26 b	0.98 b
	2400	0.72 ab	0.23 a	1.78 d	0.23 d	0.97 cd
	2800	0.63 d	0.18 dc	1.89 bc	0.26 bc	0.98 bc
	3200	0.65 cd	0.21 abc	1.76 d	0.23 d	0.97 d
	3600	0.56 e	0.17 d	1.86 bcd	0.25 bcd	0.98 bcd
MSD		0.053	0.028	0.110	0.023	0.007
Wheat straw						
90°	2000	0.90 ab	0.33 bc	1.56 ab	0.18 ab	0.97 ab
	2400	0.88 bc	0.31 bcd	1.59 ab	0.19 ab	0.97 ab
	2800	0.82 d	0.31 bcd	1.50 ab	0.17 ab	0.96 ab
	3200	0.82 d	0.30 bcd	1.52 ab	0.18 ab	0.96 ab
	3600	0.76 e	0.27 cd	1.58 ab	0.19 ab	0.97 ab
30°	2000	0.95 a	0.40 a	1.30 b	0.12 b	0.96 b
	2400	0.83 cd	0.32 bc	1.47 ab	0.16 ab	0.96 ab
	2800	0.88 bc	0.35 ab	1.39 b	0.14 b	0.96 b
	3200	0.76 e	0.24 d	1.77 a	0.23 a	0.98 ab
	3600	0.76 e	0.24 d	1.83 a	0.24 a	0.98 a
MSD		0.055	0.074	0.371	0.083	0.019
Corn stover						
90°	2000	0.70 ab	0.22 ab	1.80 abc	0.24 abc	0.98 bc
	2400	0.74 a	0.25 a	1.70 bc	0.22 bc	0.97 bc
	2800	0.66 b	0.17 b	2.17 a	0.31 a	1.00 a
	3200	0.67 ab	0.22 ab	1.72 bc	0.22 bc	0.97 bc
	3600	0.62 b	0.17 b	1.99 ab	0.28 ab	0.99 abc
30°	2000	0.74 a	0.20 ab	2.01 ab	0.28 ab	0.99 ab
	2400	0.68 ab	0.23 ab	1.70 bc	0.22 bc	0.97 bc
	2800	0.64 b	0.19 ab	1.86 abc	0.25 abc	0.98 abc
	3200	0.69 ab	0.24 a	1.61 c	0.20 c	0.97 bc
	3600	0.64 b	0.23 ab	1.57 c	0.19 c	0.97 c
MSD		0.074	0.066	0.377	0.081	0.022

* 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.

3.3.3. Effect of geometric mean diameter on specific energy per unit size reduction

Total specific energy per unit size reduction of switchgrass, wheat straw, and corn stover increased by 35, 29, and 45%, respectively, with an increase in speed from 2000 to 3600 rpm for 90°-hammers (Fig. 11). Total specific energy per unit size reduction values for 2000 rpm with 90°-hammers were 14.9, 19.7, and 13.5 MJ/Mg mm for switchgrass, wheat straw, and corn stover, respectively. Similarly, for 30°-hammers, total specific energy per unit size reduction increased by 33, 33, and 34% from 16.2, 20.1, and 16.7 MJ/Mg mm for switchgrass, wheat straw, and corn stover, respectively (Fig. 11). Specific energy per unit size reduction values of hammer mill output could be reduced many folds, had the input particle sizes (knife milled) determined with image analysis were used. Actual initial particle length was 5× compared to geometric mean length determined using ASABE sieves [26]. Total specific energy per unit size reduction for 90°-hammers was significantly less (95% confidence level) compared to 30°-hammers. Hence, 90°-hammers operated at 2000 rpm gave reduced energy input. Wheat straw consumed higher total specific energy per unit size reduction than

Table 3
Uniformity index, size guide number, uniformity coefficient, coefficient of gradation and distribution geometric standard deviation for hammer mill size reduction of switchgrass, wheat straw, and corn stover with 90°- and 30°-hammers.

Hammer type	Mill speed, N, rpm	Uniformity index, I_u, %*	Size guide number, N_{sg}*	Uniformity coefficient, C_u*	Coefficient of gradation, C_g*	GSD_1	GSD_2	GSD_{12}
Switchgrass								
90°	2000	8.88 abcd	76 a	3.96 bcd	1.19 bcd	1.86	2.41	2.11
	2400	8.43 cd	75 a	4.08 bc	1.20 bc	1.88	2.45	2.15
	2800	9.16 abcd	69 bc	3.89 bcd	1.19 bcd	1.84	2.38	2.09
	3200	9.51 abc	64 cd	3.81 bcd	1.19 cd	1.82	2.35	2.07
	3600	6.08 e	49 f	4.92 a	1.23 a	2.05	2.76	2.38
30°	2000	8.31 d	76 a	4.11 b	1.20 b	1.89	2.47	2.16
	2400	9.66 ab	72 ab	3.78 cd	1.18 d	1.82	2.33	2.06
	2800	8.41 cd	63 d	4.09 b	1.20 bc	1.88	2.45	2.15
	3200	9.92 a	65 cd	3.72 d	1.18 d	1.80	2.31	2.04
	3600	8.75 bcd	56 e	3.99 bcd	1.19 bcd	1.86	2.42	2.12
MSD		1.137	5.435	0.308	0.011			
Wheat straw								
90°	2000	12.76 bc	90 ab	3.22 abc	1.16 ab	1.69	2.11	1.89
	2400	12.16 bc	88 bc	3.31 abc	1.17 ab	1.71	2.15	1.92
	2800	13.64 abc	82 de	3.10 abc	1.16 ab	1.66	2.06	1.85
	3200	13.28 abc	82 def	3.15 abc	0.91 ab	1.68	2.08	1.87
	3600	12.37 bc	76 fg	3.28 abc	1.16 ab	1.71	2.13	1.91
30°	2000	17.78 a	95 a	2.67 c	1.13 b	1.56	1.87	1.71
	2400	14.24 abc	83 cd	3.03 abc	1.15 ab	1.65	2.03	1.83
	2800	15.79 ab	88 bc	2.86 bc	1.14 b	1.60	1.95	1.77
	3200	9.96 c	76 g	3.71 ab	1.18 a	1.80	2.31	2.04
	3600	9.52 c	76 efg	3.81 a	1.19 a	1.82	2.35	2.07
MSD		4.861	5.536	0.961	0.039			
Corn stover								
90°	2000	9.38 abc	70 ab	3.84 bcd	1.19 abc	1.83	2.36	2.08
	2400	10.73 ab	74 a	3.56 bcd	1.18 bc	1.77	2.25	1.99
	2800	6.20 c	66 ab	4.86 a	1.22 a	2.04	2.74	2.36
	3200	10.37 abc	67 ab	3.63 bcd	1.18 bc	1.78	2.28	2.02
	3600	7.56 bc	62 b	4.34 abc	1.21 ab	1.93	2.55	2.22
30°	2000	7.35 bc	74 a	4.41 ab	1.21 ab	1.95	2.58	2.24
	2400	10.65 ab	68 ab	3.57 bcd	1.18 bc	1.77	2.25	2.00
	2800	8.79 abc	64 b	3.98 abcd	1.19 abc	1.86	2.42	2.12
	3200	12.08 a	69 ab	3.33 cd	1.17 c	1.72	2.15	1.92
	3600	12.72 a	64 b	3.23 d	1.16 c	1.69	2.11	1.89
MSD		4.424	7.812	1.037	0.039			

* 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.

switchgrass and corn stover for both the hammer types. Flexible nature of wheat straw compared to switchgrass and corn stover was attributed to more total specific energy per unit size reduction.

Effective specific energy per unit size reduction of switchgrass and wheat straw decreased gradually by 5 and 23% from 7.5 and 10.8 MJ/Mg mm, respectively for 90°-hammers with an increase in speed from 2000 to 3600 rpm (Fig. 12). On the other hand, it increased by 25% from 6.1 MJ/Mg mm for corn stover. However, effective specific energy per unit size reduction consumed for 30°-hammers increased marginally with speed to a certain extent and then decreased (Fig. 12).

3.3.4. Cumulative size distribution

Cumulative undersize mass percentage as a function of switchgrass, wheat straw, and corn stover particle diameter, assumed equivalent to nominal sieve opening size, did not show straight line over log–probability plots in Figs. 13–15, respectively, which represented bimodal distribution of particles [37]. Further, there was optical cutoff observed on log–log scale (not shown) as particles were fine in size, but aerodynamic cutoff was not observed. By definition, optical and aerodynamic cutoff of size distribution means the curving down of lower end and curving up of upper end of log–probability curve, respectively [37]. Overall, cumulative trends for mill speeds from 2000 to 3600 rpm were said to be 'well-graded'. No distribution was 'poorly' or 'gap' ('step') graded. In the present study, distribution curves showed effect of mixture of two or more log-normal distributions having two or more geometric standard deviations but of different median sizes for speeds tested.

3.3.5. Rosin–Rammler parameters

Rosin–Rammler parameters considered 100% of the particle mass. Rosin–Rammler size parameter, a (an intercept of equation), of switchgrass, wheat straw, and corn stover decreased with an increase in speed from 2000 to 3600 rpm for 90°-hammers (Fig. 16). A similar decrease was observed for 30°-hammers. Size parameter was always greater than median diameter, which was greater than geometric mean diameter (Tables 1 and 2). This trend was due to positive skewness (fine skewed) of distribution, median diameter determined from fitted curvilinear trend, and geometric mean calculated based on linear portion of the data points [29]. 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). Mean separation of size parameter formulated seven coherent groups for switchgrass, six for wheat straw, and five for corn stover (Table 1). Rosin–Rammler size parameter had strong negative correlation with speed for switchgrass (−0.945) (Table 4) and wheat straw (−0.902) (data not presented) and good correlation for corn stover (−0.814) (data not presented).

Rosin–Rammler distribution parameter, b (slope of equation), did not exhibit a specific trend like geometric standard deviation (Table 1). Further, increased distribution parameter represented more uniformity of particles. For example, distribution curve of 2000 rpm, 90°-hammer, switchgrass ($b=1.57$) was more uniform than 2400 rpm, 90°-hammer, switchgrass ($b=1.54$) even though they have equal Rosin–Rammler size parameter of 0.96 mm (Table 1). Thus, kurtosis values (Table 2) were inversely proportional to distribution parameter (Table 1) and

Table 4
Pearson correlation coefficients for hammer mill size reduction of switchgrass with 90°- and 30°-hammers.

Parameter	Hammer type	Speed, N, rpm	Total specific energy, E_t, kWh/Mg	Effective specific energy, E_e, kWh/Mg	Geometric mean diameter, 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	Inclusive graphic skewness, GS_i	Graphic kurtosis, K_g	Uniformity index, I_u, %	Uniformity coefficient, C_u	Coefficient of gradation, C_g	Distribution standard deviation (total), GSD_{12}
Hammer	1.000																
N	0.000 (1.000)	1.000															
E_t	0.220 (0.542)	0.968 $(<10^{-4})$	1.000														
E_e	0.821 (0.004)	−0.222 (0.011)	0.020 (0.957)	1.000													
X_{gm}	0.000 (1.000)	−0.914 (2E−4)	−0.883 (7E−4)	0.272 (0.446)	1.000												
S_{gm}	−0.262 (0.465)	−0.056 (0.877)	−0.085 (0.815)	−0.276 (0.440)	−0.291 (0.414)	1.000											
a	−0.025 (0.945)	−0.945 $(<10^{-4})$	−0.914 (2E−4)	0.247 (0.491)	0.991 $(<10^{-4})$	−0.167 (0.644)	1.000										
b	0.295 (0.408)	−0.242 (0.500)	−0.195 (0.589)	0.333 (0.348)	0.552 (0.098)	−0.928 (1E−4)	0.447 (0.195)	1.000									
D_{50}	−0.002 (0.997)	−0.929 (1E−4))	−0.895 (5E−4)	0.264 (0.461)	0.997 $(<10^{-4})$	−0.236 (0.512)	0.997 $(<10^{-4})$	0.511 (0.131)	1.000								
D_{10}	0.087 (0.811)	−0.817 (0.004)	−0.776 (0.008)	0.314 (0.377)	0.971 $(<10^{-4})$	−0.486 (0.154)	0.936 $(<10^{-4})$	0.731 (0.016)	0.959 $(<10^{-4})$	1.000							
RS_m	−0.302 (0.396)	0.281 (0.431)	0.233 (0.517)	−0.339 (0.339)	−0.584 (0.077)	0.922 (2E−4)	−0.482 (0.158)	−0.997 $(<10^{-4})$	−0.544 (0.104)	−0.755 (0.012)	1.000						
GS_i	−0.299 (0.401)	0.268 (0.454)	0.220 (0.540)	−0.336 (0.343)	−0.573 (0.083)	0.925 (1E−4)	−0.470 (0.170)	−0.999 $(<10^{-4})$	−0.533 (0.113)	−0.747 (0.013)	0.999 $(<10^{-4})$	1.000					
K_g	−0.304 (0.393)	0.313 (0.379)	0.264 (0.460)	−0.342 (0.334)	−0.608 (0.062)	0.913 (2E−4)	−0.510 (0.132)	−0.989 $(<10^{-4})$	−0.570 (0.085)	−0.771 (0.009)	0.998 $(<10^{-4})$	0.996 $(<10^{-4})$	1.000				
I_u	0.294 (0.410)	−0.233 (0.517)	−0.187 (0.606)	0.331 (0.350)	0.544 (0.104)	−0.929 (1E−4)	0.439 (0.205)	1.000 $(<10^{-4})$	0.503 (0.139)	0.725 (0.018)	−0.995 $(<10^{-4})$	−0.998 $(<10^{-4})$	−0.987 $(<10^{-4})$	1.000			
C_u	−0.303 (0.395)	0.295 (0.407)	0.247 (0.491)	−0.340 (0.337)	−0.595 (0.070)	0.918 (2E−4)	−0.495 (0.146)	−0.994 $(<10^{-4})$	−0.556 $(<10^{-4})$	−0.762 (0.010)	1.000 $(<10^{-4})$	0.998 $(<10^{-4})$	0.999 $(<10^{-4})$	−0.992 $(<10^{-4})$	1.000		
C_g	−0.301 (0.398)	0.277 (0.439)	0.229 (0.525)	−0.337 (0.341)	−0.580 (0.079)	0.923 (1E−4)	−0.479 (0.162)	−0.998 $(<10^{-4})$	−0.541 (0.107)	−0.752 (0.012)	1.000 $(<10^{-4})$	1.000 $(<10^{-4})$	0.997 $(<10^{-4})$	−0.996 $(<10^{-4})$	0.999 $(<10^{-4})$	1.000	
GSD_{12}	−0.302 (0.397)	0.286 (0.423)	0.238 (0.508)	−0.338 (0.339)	−0.587 (0.074)	0.921 (2E−4)	−0.486 (0.154)	−0.996 $(<10^{-4})$	−0.548 (0.101)	−0.757 (0.011)	1.000 $(<10^{-4})$	0.999 $(<10^{-4})$	0.998 $(<10^{-4})$	−0.994 $(<10^{-4})$	1.000 $(<10^{-4})$	1.000 $(<10^{-4})$	1.000

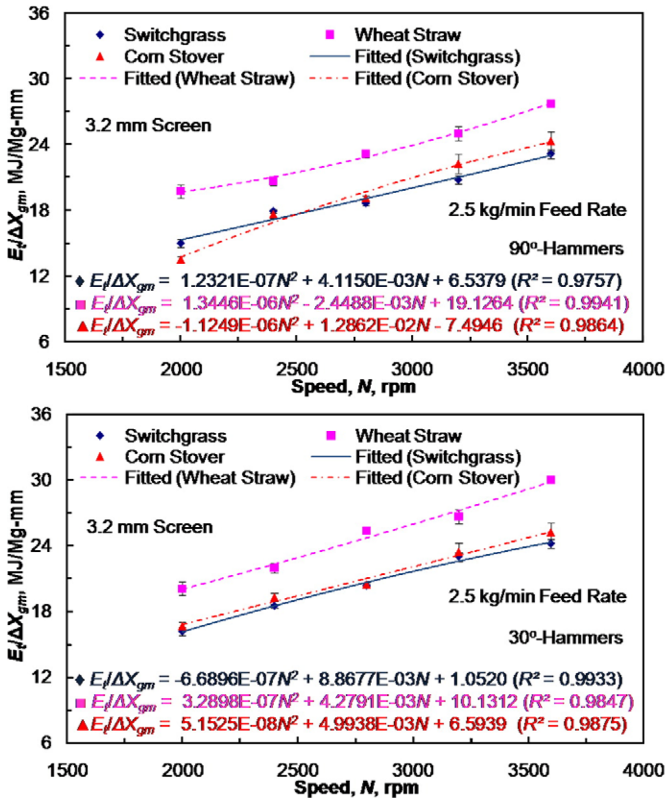

Fig. 11. Variation in total specific energy per unit size reduction of switchgrass, wheat straw, and corn stover hammer mill grind with speed for 90°- and 30°-hammers.

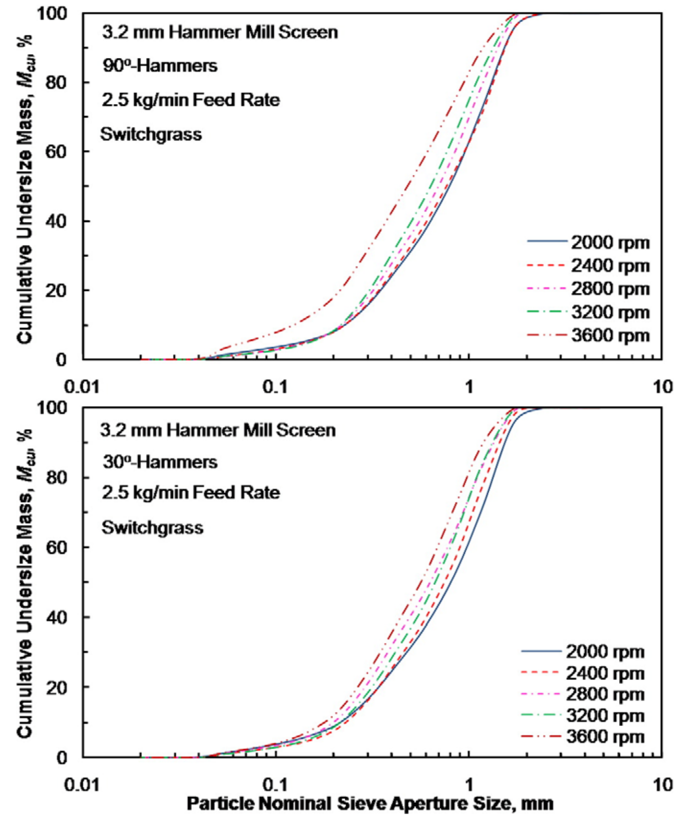

Fig. 13. Cumulative percent undersize switchgrass hammer mill grind with 90°- and 30°-hammers.

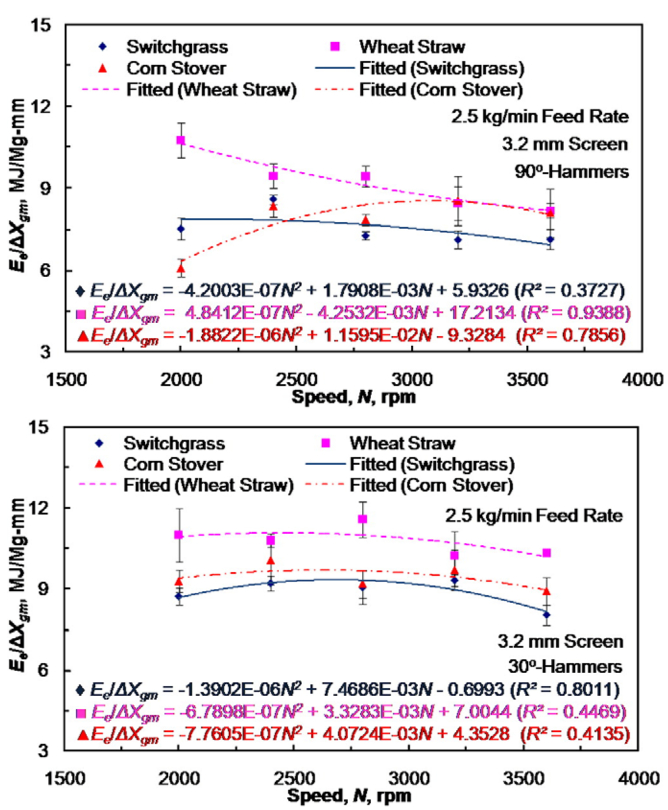

Fig. 12. Variation in effective specific energy per unit size reduction of switchgrass, wheat straw, and corn stover hammer mill grind with speed for 90°- and 30°-hammers.

directly proportional to mass relative span (Table 2). This means, a reduced distribution parameter indicated wide distribution. In all cases, Rosin–Rammler equations were fitted with high $R^2>0.995$. This agrees with published trends [29–31]. Increased coefficient of determination indicated that particle size distribution of switchgrass, wheat straw, and corn stover 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 [40]. Mean separation of distribution parameter resulted in five uniform groups for switchgrass, but three groups each for wheat straw and corn stover (Table 1). Rosin–Rammler distribution parameter had moderate negative correlation with speed for wheat straw (−0.618) (data not presented), but weak correlation for switchgrass (Table 4) and corn stover (data not presented).

3.3.6. Median diameter, effective size and mass relative span

Median diameter, D_{50}, of switchgrass, wheat straw, and corn stover decreased with an increase in speed from 2000 to 3600 rpm for 90°-hammers (Table 2). A similar trend was observed for 30°-hammers. Median diameter was greater than geometric mean diameter (Tables 1 and 2). Fine skewness of distribution was the reason for reduced geometric mean than median value. Mean separation of median diameter indicated six, five, and two uniform groups for switchgrass, wheat straw, and corn stover, respectively. Median diameter had strong negative correlation with speed for switchgrass (−0.929) (Table 4) and wheat straw (−0.897) (data not presented), and good correlation for corn stover (−0.761) (data not presented). Effective size was less than median diameter as it should be mathematically (Table 2). Effective size of switchgrass, wheat straw, and corn stover decreased with an increase in speed from 2000 to 3600 rpm for 90°-hammers (Table 2). A similar trend was observed for 30°-hammers.

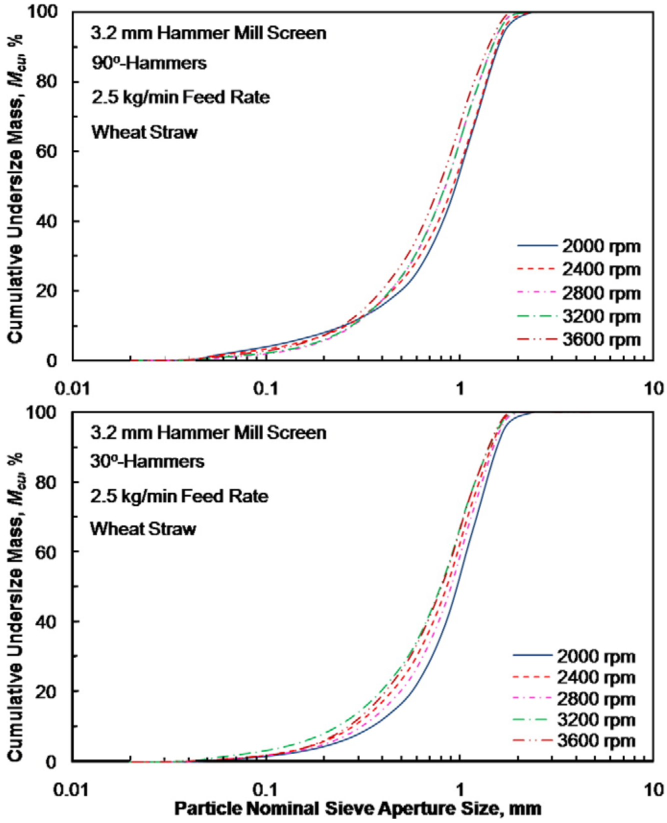

Fig. 14. Cumulative percent undersize wheat straw hammer mill grind with 90°- and 30°-hammers.

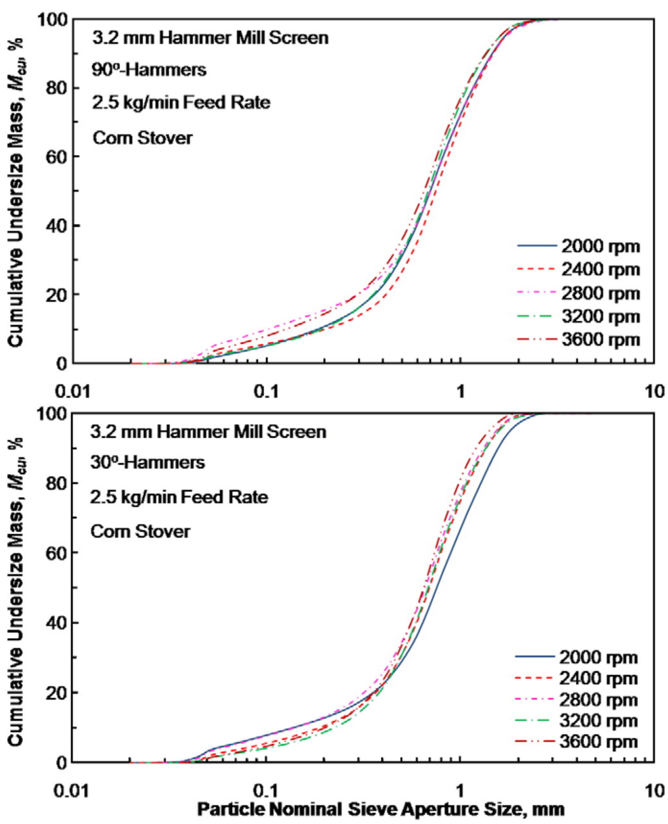

Fig. 15. Cumulative percent undersize corn stover hammer mill grind with 90°- and 30°-hammers.

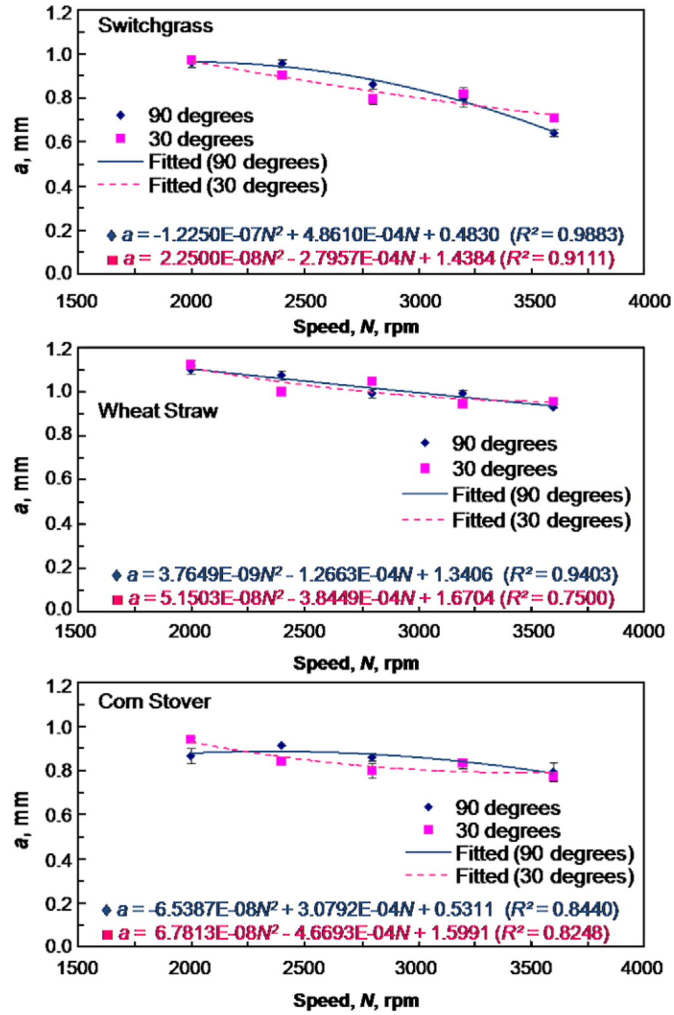

Fig. 16. Variation in Rosin–Rammler size parameter of hammer mill switchgrass, wheat straw, and corn stover grind with speed for 90°- and 30°-hammers.

Mean separation of effective size indicated five, four, and two similar groups for switchgrass, wheat straw, and corn stover, respectively. Effective size had good negative correlation with speed for switchgrass (−0.817) (Table 4) and wheat straw (−0.789) (data not presented), and weak correlation for corn stover (data not presented).

Mass relative span, RS_m, of switchgrass, wheat straw, and corn stover, which accounted for 80% particle mass, did not follow specific trend with an increase in speed from 2000 to 3600 rpm (Table 2). Decrease in span indicated narrow distribution of particles, which means skewness decreased. It was also noted that relative span was inversely proportional to Rosin–Rammler distribution parameter. But, span was greater than 1.0 for all speeds, which indicated as such a wide distribution of particles. Himmel et al. [13] also observed wide distribution of wheat straw grind and aspen chips prepared with small size screens. Mean separation of span indicated uniformly size distributed particles which were differently sized with more or less similar weight fractions retained on each sieve. It formed four, two, and three coherent groups for switchgrass, wheat straw, and corn stover, respectively. Relative span had moderate positive correlation with speed for wheat straw (0.626) (data not presented) and weak correlation for switchgrass (Table 4) and corn stover (data not presented).

3.3.7. Skewness and kurtosis

Of particular interest, hammer mill speeds determined characteristic shapes in particle spectra curves (Figs. 7–9). Inclusive graphic skewness, GS_i, values of switchgrass, wheat straw, and corn stover, which included 90% of particle mass, could not show specific trend with an increase in speed from 2000 to 3600 rpm (Table 2). All speeds of hammer mill yielded 'fine-skewed' switchgrass, wheat straw, and corn stover particles, as values were between +0.3 and +0.1 [42]. Mean separation of skewness followed almost similar grouping of relative span (Table 2). Graphic kurtosis, K_g, values of switchgrass, wheat straw, and corn stover, which included 90% of particle mass, did not follow specific trend with speed (Table 2). Decreased kurtosis or peakedness means increase in uniformity index (Table 3). Increased uniformity was the reason for increased Rosin–Rammler distribution parameter and decreased mass relative span. Switchgrass, wheat straw, and corn stover particles from all speeds and hammers were termed as 'mesokurtic', as kurtosis was within 0.90 and 1.11 [42]. Mesokurtic distribution is a distribution with same degree of peakedness about the mean as a normal distribution. Hence, hammer mill grinding of switchgrass, wheat straw, and corn stover with 3.2 mm screen resulted in 'fine-skewed mesokurtic' particles. Mean separation of kurtosis resulted in four, two, and three coherent groups for switchgrass, wheat straw, and corn stover, respectively, similar to relative span and in reverse order with Rosin–Rammler distribution parameter (Tables 1 and 2). Skewness and kurtosis had moderate correlation of 0.622 and 0.611 with speed, respectively, for wheat straw (data not presented) and weak correlation for switchgrass (Table 4) and corn stover (data not presented).

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

Uniformity index, I_u, of switchgrass, wheat straw, and corn stover did not follow a specific trend with speed (Table 3). However, increased uniformity index was attributed to decrease in relative span and skewness. Uniformity index of particle size distribution, which accounted for 85% of particle mass, was very low (<80%) for all samples (Table 3), due to fine skewness of particles. Mean separation of uniformity index resulted in five, three, and three uniform groups for switchgrass, wheat straw, and corn stover, respectively. Speed had moderate negative correlation with uniformity index for wheat straw (−0.617) (data not presented). Size guide number, N_{sg}, of switchgrass, wheat straw, and corn stover decreased with an increase in speed from 2000 to 3600 rpm (Table 3). Size guide number had mean separation similar to median diameter, as it was differed by a factor of 100 (Tables 2 and 3).

Uniformity coefficient, C_u, of switchgrass, wheat straw, and corn stover did not show specific trend with an increase in speed (Table 3). Uniformity coefficient of 1.0 denotes particles of same/equivalent size. Numbers greater than 1.0 denotes reduced uniformity. Material with a uniformity coefficient of <4.0 contains particles of approximately uniform size [38]. Uniformity coefficient was <4.0 for wheat straw, which indicated uniform mix of particles, and it was about 4.0 for switchgrass and corn stover, which indicated a moderate assortment of particle size. This also represented a well-graded particle size distribution as indicated by gradually increasing cumulative distribution curves (Figs. 13–15). Uniformity coefficient, which accounted for 50% of particle mass, was inversely proportional to uniformity index (Table 3) with a correlation coefficient of −0.992 (Table 4), −0.986 (data not presented), and −0.987 (data not presented) for switchgrass, wheat straw, and corn stover, respectively. Mean separation of uniformity coefficient resulted in four, three, and four similar groups for switchgrass, wheat straw, and corn stover. Allaire and Parent [30] also found uniformity coefficient as the least discriminating distribution parameter. Uniformity coefficient had moderate correlation with speed for wheat straw (0.624) (data not given) and weak correlation for switchgrass (Table 4) and corn stover (data not given).

Coefficient of gradation, C_g, which accounted for 50% of particle mass, could not draw specific trend with an increase in speed (Table 3). Coefficient of gradation between 1 and 3 represents well-graded particles [38] as observed in the present study. Mean separation of coefficient of gradation resulted in four, two, and three coherent groups for switchgrass, wheat straw, and corn stover, respectively, similar to relative span and skewness (Tables 2 and 3) as correlation coefficient was 1.0 between them (Table 4, data not presented for wheat straw and corn stover). Coefficient of gradation had moderate correlation with speed, N (0.624) while wheat straw grinding (data not presented).

3.3.9. Distribution geometric standard deviation

Bimodal distribution between cumulative undersize mass and sieve opening size was observed on log–log plots for Figs. 13–15. Distribution geometric standard deviation of total region, GSD_{12}, high and low regions as well, did not follow specific trend with an increase in speed (Table 3). However, distribution geometric standard deviation had moderate correlation with speed while wheat straw grinding (0.624) (data not presented). Hence, use of distribution geometric standard deviation improved the relation with mill speed, compared to using geometric standard deviation.

3.4. Correlations

A positive strong correlation was established between hammer mill speed and total specific energy (>0.960) for three biomasses tested. A good correlation was established between hammer type and effective specific energy (0.821, 0.742, and 0.768 for switchgrass, wheat straw, and corn stover, respectively) (Table 4, data not presented for wheat straw and corn stover). A direct consistent relation was observed among size-related parameters namely, geometric mean diameter, X_{gm}, Rosin–Rammler size parameter, a, median diameter, D_{50}, and effective size, D_{10} for switchgrass (Table 4), wheat straw (data not presented), and corn stover (data not presented). A strong positive correlation existed among distribution-related parameters, namely, geometric standard deviation, S_{gm}, mass relative span, RS_m, inclusive graphic skewness, GS_i, graphic kurtosis, K_g, uniformity coefficient, C_u, coefficient of gradation, C_g, and distribution geometric standard deviation, GSD_{12}, and also among Rosin–Rammler distribution parameter, b, and uniformity index, I_u. These two sets of distribution-related parameters had strong negative correlation (Table 4).

4. Conclusions

No-load power demand of hammer mill increased curvilinear by 66% from 1.72±0.02 kW with an increase in speed from 1500 to 3500 rpm. Total specific energy of switchgrass, wheat straw, and corn stover increased by 37, 30, and 45%, respectively, with an increase in hammer mill speed from 2000 to 3600 rpm for 90°-hammers. There was an increase in total specific energy while grinding with 30°-hammers compared to 90°-hammers. Effective specific energy of 90°-hammers was less at all speeds compared to 30°-hammers. Optimum total specific energies of 114.4, 125.1, and 103.7 MJ/Mg for switchgrass, wheat straw, and corn stover, respectively, were obtained for 2000 rpm for mass feed rate of 2.5 kg/min and 3.2 mm screen with 90°-hammers (6.4 mm-thick). The corresponding total specific energy per unit size reduction was 14.9, 19.7, and 13.5 MJ/Mg mm, respectively. Hammer mill produced coarse wheat straw particles compared to switchgrass and corn stover. Hammer milling of switchgrass, wheat straw, and corn stover with 3.2 mm screen resulted in 'well-graded fine-skewed mesokurtic' particles for all speeds. Rosin–Rammler equations fitted the size distribution data with high R^2>0.995. Uniformity coefficient was <4.0 for wheat straw, which indicated uniform mix of particles, and it was about 4.0 for switchgrass and corn stover, which indicated a moderate assortment of particle size. A positive strong correlation was established between hammer mill speed and total specific energy. A good correlation was established between hammer type and effective specific energy. Geometric mean diameter, Rosin–Rammler size parameter, median diameter, and effective size had strong correlation among themselves and negative correlation with speed. Distribution related parameters, namely, geometric standard deviation, mass relative span, Rosin–Rammler distribution parameter, inclusive graphic skewness, graphic kurtosis, uniformity index, uniformity coefficient, coefficient of gradation, and distribution geometric standard deviation had strong correlation among themselves and a weak correlation with mill speed. Analysis of size reduction specific energy and particle size distribution will lead to the selection of hammer mill operating speed to produce a particular particle size of switchgrass, wheat straw and corn stover grind.

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References

[1] N. Greene, Growing Energy — How Biofuels Can Help End America's Oil Dependence, National Resources Defense Council, NY, 2004.
[2] A. Kumar, S. Sokhansanj, Switchgrass (*Panicum vigratum* L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model, Bioresour. Technol. 98 (2007) 1033–1044.
[3] U.S. Patent 5 677 154, Production of ethanol from biomass, USA, 1997.
[4] Z. Drzymala, Industrial briquetting — fundamentals and methods, Studies in Mechanical Engineering, vol. 13, PWN-Polish Scientific Publishers, Warszawa, 1993.
[5] D.J. Schell, C. Harwood, Milling of lignocellulosic biomass: results of pilot scale testing, Appl. Biochem. Biotechnol. 45/46 (1994) 159–168.
[6] US Department of Energy, Assessment of costs and benefits of flexible and alternative fuel use in the US transportation sector, in: Evaluation of a Wood-to-Ethanol Process, Technical Report No. 11, DOE/EP-0004, US Department of Energy, Washington, DC, 1993.
[7] A. Aden, M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallance, Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover, NREL/TP-510-32438, National Renewable Energy Laboratory, USA, 2002.
[8] R.A. Silverstein, Y. Chen, R.R.S. Shivappa, M.D. Boyette, J. Osborne, A comparison of chemical pretreatment methods for improving saccharification of cotton stalks, Bioresour. Technol. 98 (2007) 3000–3011.
[9] S. Mani, L.G. Tabil, S. Sokhansanj, Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass, Biomass Bioenergy 27 (2004) 339–352.
[10] S. Mani, L.G. Tabil, S. Sokhansanj, Grinding performance and physical properties of selected biomass, ASAE Paper No. 02-6175, ASAE, St. Joseph, MI, 2002.
[11] R. Datta, Energy requirement for lignocellulose pretreatment processes, Process Biochem. 16 (1981) 16–19 June/July 42.
[12] R.L. Scholten, R.R. McEllhiney, The effects of prebreaking in hammer mill particle size reduction, ASAE Paper No. 85-3542, ASAE, St. Joseph, MI, 1985.
[13] M. Himmel, M. Tucker, J. Baker, C. Rivard, K. Oh, K. Grohmann, Comminution of biomass: hammer and knife mills, Biotechnol. Bioeng. Symposium, vol. 15, 1985, pp. 39–58.
[14] L.G. Austin, R.R. Klimpel, The theory of grinding, Ind. Eng. Chem. 56 (1964) 18–29 November.
[15] W.A. Balk, Energy requirements for dehydrating and pelletizing coastal bermuda-grass, Trans. ASAE 4 (1964) 349–351 355.
[16] J.F. Arthur, R.A. Kepner, J.B. Dobie, G.E. Miller, P.S. Parsons, Tub grinder performance with crop and forest residues, Trans. ASAE 25 (1982) 1488–1494.
[17] P. Samson, P. Duxbury, M. Drisdelle, C. Lapointe, Assessment of Pelletized Biofuels, PERD Program, National Resources Canada, Contract 23348-8-3145/001/SQ, 2000.
[18] R. Jannasch, Y. Quan, R. Samson, A Process and Energy Analysis of Pelletizing Switchgrass, Final Report, Natural Resources Canada, 2001.
[19] L.S. Esteban, J.E. Carrasco, Evaluation of different strategies for pulverization of forest biomasses, Powder Technol. 166 (2006) 139–151.
[20] L. Cadoche, G.D. López, Assessment of size reduction as a preliminary step in the production of ethanol for lignocellulosic wastes, Biol. Wastes 30 (1989) 153–157.
[21] C. Vigneault, T.M. Rothwell, G. Bourgeois, Hammer mill grinding rate and energy requirements for thin and conventional hammers, Can. Agric. Eng. 34 (1992) 203–206.
[22] Agriculture Canada, Size reduction, Agricultural Materials Handling Manual, Agriculture Canada, Ottawa, ON, 1971.
[23] V. Bargen, M. Lamb, D.E. Neals, Energy requirements for particle size reduction of crop residues, ASAE Paper No. 81-4062, ASAE, St. Joseph, MI, 1981.
[24] W. Yang, S. Sokhansanj, W.J. Crerer, S. Rohani, Size and shape related characteristics of alfalfa grind, Can. Agric. Eng. 38 (1996) 201–205.
[25] S. Mani, L.G. Tabil, S. Sokhansanj, Mechanical properties of corn stover grind, Trans. ASAE 47 (2004) 1983–1990.
[26] A.R. Womac, C. Igathinathane, P. Bitra, P. Miu, T. Yang, S. Sokhansanj, S. Narayan, Biomass pre-processing size reduction with instrumented mills, ASABE Paper No. 076046, ASABE, St. Joseph, MI, 2007.
[27] Y. Yang, A.R. Womac, P.I. Miu, High-specific separation of biomass materials by sieving, ASABE Paper No. 066172, ASABE, St. Joseph, MI, 2006.
[28] P. Rosin, E. Rammler, The laws governing the fineness of powdered coal, J. Instr. Fuel 7 (1933) 29–36.
[29] E. Perfect, Q. Xu, Improved parameterization of fertilizer particle size distribution, J. AOAC Int. 81 (1998) 935–942.
[30] S.E. Allaire, L.E. Parent, Size guide and Rosin–Rammler approaches to describe particle size distribution of granular organic-based fertilizers, Biosyst. Eng. 86 (2003) 503–509.
[31] S. Jaya, T.D. Durance, Particle size distribution of alginate-pectin microspheres: effect of composition and methods of production, ASABE Paper No. 076022, ASABE, St. Joseph, MI, 2007.
[32] ASABE Standards, Moisture measurement — forages ASABE S358.2, ASABE Standards 2006, American Society of Agricultural and Biological Engineers, St. Joseph, MI, USA, 2006, p. 608.
[33] H.Y. Jeon, A.R. Womac, J.B. Wilkerson, W.E. Hart, Sprayer boom instrumentation for field use, Trans. ASAE 47 (2004) 659–666.
[34] J. Proakis, D. Manolakis, Digital Signal Processing: Principles, Algorithms, and Applications, Macmillan Publishing Co., NY, 1992.
[35] ASABE Standards, Method of determining and expressing fineness of feed materials by sieving ANSI/ASABE S319.3, ASABE Standards 2006, American Society of Agricultural and Biological Engineers, St. Joseph, MI, USA, 2006, p. 602.
[36] M.T. Holtzapple, A.E. Humphrey, J.D. Taylor, Energy requirements for the size reduction of poplar and aspen wood, Biotechnol. Bioeng. 33 (1989) 207–210.
[37] W.C. Hinds, Aerosol Technology — Properties, Behaviour, and Measurement of Airborne Particles, John Wiley & Sons, NY, 1982.
[38] M. Budhu, Soil Mechanics and Foundations, second ed., John Wiley & Sons, Inc., Danvers, MA, 2007.
[39] R.F. Craig, Craig's Soil Mechanics, Spon Press, London, 2004.
[40] K.M. Djamarani, I.M. Clark, Characterization of particle size based on fine and coarse fractions, Powder Technol. 93 (1997) 101–108.
[41] I. Allais, R. Edoura-Gaena, J. Gros, G. Trystram, Influence of egg type, pressure and mode of incorporation on density and bubble distribution of a lady finger batter, J. Food Eng. 74 (2006) 198–210.
[42] R.L. Folk, Petrology of Sedimentary Rocks, Hemphill Publishing Co., Austin, Texas, 1974.
[43] CFI, The CFI Guide of Material Selection for the Production of Quality Blends, Canadian Fertilizer Institute, Ottawa, Ontario, Canada, 1982.
[44] SAS, SAS/Stat User's Guide, Version 9.1, SAS Institute, Inc., Cary, NC, USA, 2004.
[45] H. Pfost, V. Headley, Methods of determining and expressing particle size, in: H.B. Pfost, D. Pickering (Eds.), Feed Manufacturing Technology, Arlington, American Feed Manufacturers Association, Inc., Virginia, 1976, pp. 512–517.