Study of Corn Stover Particle Size Distribution Characteristics for Knife Mill and Hammer Mill

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Abstract. Corn stover is a major agricultural biomass feedstock. The particle size distribution (PSD) of ground corn stover is important for biomass to bioenergy conversion. The objectives of this study were to evaluate Rosin-Rammler (RR) distribution, normal distribution and lognormal distribution on analysing PSD of corn stover grinded by knife mill and hammer mill, and to compare the grinding performance for knife mill and hammer mill. RR distribution model provided the best fitting results (0.998≤ Adj. R²≤1) to the ground corn stover among the three PSD distribution models. The grinding performance based on the characteristic parameters (geometric mean diameter, geometric standard deviation, RR distribution parameter) analysis for the knife mill is better than the hammer mill for grinding corn stover under the same conditions.

1. Introduction

Corn stover is considered as an extensively distributed and abundant biomass feedstock in the world[1]. According to the relevant data from National Bureau of Statistics, corn planting area reached more than 40 million hectares in China[2]. Size reduction is an important operation for corn stover conversion and can also help to reduce transportation costs. Size reduction process changes the particle size and shape, improves flowability, increases loose bulk density, and creates new specific surface area[3]. Particle size has a great impact on the applications in many areas such as densification, fluidization, pyrolysis and combustion[4]. Therefore, to describe particle size distribution (PSD) precisely is in need for corn stover efficient utilization.

Any single dimension definition for particle size, screen size or geometric mean diameter, is not sufficient to precisely describe the PSD. Thus, mathematical models are applied to describe the PSD of grinded biomass. Certain coefficients in mathematical models are helpful for analysing the PSD characteristics[5]. Many mathematical models with varying complexity have been developed to determine the PSD. Rosin-Rammler (RR) distribution has been used in comminution industry[6]. Normal distribution and lognormal distribution have been widely applied in natural and social sciences. Venkata et al found the RR distribution was suitable for the switchgrass PSD in the analysis the operating factors effect of knife mill[7]; Williams et al reported the RR distribution had been well fit for biomass comminution in a knife mill[8]; The RR distribution provided best results when applied to the agglomerated cork particles[9]. PSD of alfalfa grinded by hammer mill was fitted with a lognormal distribution studied by Yang et al[10]. The knife mill and hammer mill were commonly used in biomass size reduction[11]. PSD is subject to certain statistical law for the size reduction process in the previous studies. However, there is a gap on selecting the best fitting model for corn stover PSD based on the existing model comparison. Thus, the study aims to: 1) evaluate three models: Rosin-Rammler (RR)
distribution, normal distribution and lognormal distribution on analysing PSD of corn stover grinded by knife mill and hammer mill, 2) and to compare the grinding performance of knife mill and hammer mill.

2. Materials and methods

2.1 Feedstock
Corn plants were planted in the experimental field of Shenyang Agricultural University and harvest manually in September 2017. Corn stover were naturally dried in the laboratory at an average temperature about 20°C for 10 months before experiments. Prior to the test, the moisture content of corn stover was measured at 8.52% (d.b.) according to the ANSI/ASAE standard S358.3[12].

2.2 Experimental procedure
The comminution trails were conducted using knife mill and hammer mill (both models are 30B, Weihai, China) respectively. Both mills are continuous throughput mills with a set of three circular openings (3.2, 6.3 and 12.7mm) screens. Approximately 500 g of corn stover was grinded each time under different screen size, and the corn stover particles were placed in the zip-lock bag for sieving. The electric sieve shaker (8411, Zhejiang, China) was used for sieving according to the ANSI/ASAE S319.4 sieving standard[13]. 100±0.1g sample from the zip-lock bag was weighed, the sample was placed on the top sieve of the multi-layer sieve and vibrated for 10 minutes. The sample on each sieve was collected and weighed for further the experimental PSD measurement, which represented the percentages of weight to the corresponding particle size.

2.3 PSD models
RR distribution is an exponential distribution. The RR distribution was:
\[ R(x) = 100 - 100\exp(-bx^m) = 100 - 100\exp(-x / x_e^m) \] (1)
where \( R(x) \) is the cumulative weight of particles smaller than \( x(\mu m) \); \( x_e \) is the characteristic particle size of RR distribution (mm); \( b \) and \( m \) are the distribution parameter (dimensionless).

Normal distribution has been successfully used in many fields. The normal distribution was:
\[ f(x) = \frac{A_{nor}}{\delta_{nor}\sqrt{2\pi}} \exp\left(-\frac{(x - \mu_{nor})^2}{2\delta_{nor}^2}\right) \] (2)
where \( f(x) \) is the probability density; \( A_{nor} \) is the peak curve coefficient; \( \mu_{nor} \) is the arithmetic mean of \( x \); \( \delta_{nor} \) is the standard deviation of \( x \).

Lognormal can be used to describe the distribution with skewed curves. The log-normal distribution was:
\[ f(x) = \frac{A_{log}}{x\delta_{log}\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \ln \mu_{log})^2}{2\delta_{log}^2}\right) \] (3)
where \( f(x) \) is the probability density; \( A_{log} \) is the peak curve coefficient; \( \mu_{log} \) is the arithmetic mean of \( \ln x \); \( \delta_{log} \) is the standard deviation of \( \ln x \).

2.4 Evaluation methods
The coefficients of all equations were estimated using the Curve Fitting Toolbox of Matlab R2014a software (The MathWorks, Inc.). \( Adj.R^2 \) was used to evaluate the model fitting performance.
\[ Adj.R^2 = 1 - \frac{(1 - R^2)(N - 1)}{(N - p - 1)} \] (4)
where \( Adj. R^2 \) is calculated from the coefficient of determination; \( R^2 \) is the coefficient of determination. \( N \) is the number of experimental data number; \( p \) is the degree of freedom of the model (RR distribution \( p = 2 \), normal and lognormal distribution \( p = 3 \)).
2.5 Sieving data analysis

Geometric mean diameter or median size of particles by mass, \( d_{gw} \), and geometric standard deviation of log-normal distribution by mass in ten-based logarithm, \( S_{log} \), were calculated based on mass fraction using the following equations.

\[
d_{gw} = \log^{-1} \left[ \sum_{i=1}^{n} \left( W_i \log \sqrt{d_i \cdot d_{i+1}} \right) \right] / \left[ \sum_{i=1}^{n} W_i \right]
\]

\[
S_{log} = \left[ \sum_{i=1}^{n} W_i \left( \log \sqrt{d_i \cdot d_{i+1}} - \log d_{gw} \right)^2 \right] / \left[ \sum_{i=1}^{n} W_i \right]
\]

where \( d_i \) is the \( i^{th} \) sieve (mm); \( W_i \) is the mass on \( i^{th} \) sieve (g).

3. Results and discussion

3.1 Fitting result

The PSD curves of corn stover grinded by the knife mill and hammer mill with different screen were shown in Fig. 1 (e.g. KM3.2 represented knife mill with 3.2mm screen size). The results of fitting RR distribution, normal distribution and lognormal distribution coefficients were listed in Table 1. The coefficients \( b, \delta_{nor} \) and \( \delta_{log} \) represented the width of RR, normal and lognormal distributions, respectively. For the RR distribution, the value of coefficient \( b \) was smaller for the corn stover particle with larger characteristic particle size \( x_c \). For the normal and log-normal distribution, the value of coefficients \( \delta_{nor} \) and \( \delta_{log} \) were smaller for the corn stover particle with larger mean particle size (\( \mu_{nor} \) and \( \mu_{log} \)). This was consistent with the shapes of PSD curve (Fig.1).

![Figure 1. Corn stover PSD grinded by knife mill (KM) and hammer mill (HM)](image-url)
Table 1. Fitting coefficients of RR, Normal and Lognormal distribution model for corn stover particles

| Sample | x_e | m   | b    | A
|--------|-----|------|------|-------|
|        |     |      |      | normal |
| KM3.2  | 0.697 | 2.113 | 2.143 | 26.776 | 0.39 | 0.633 | 31.272 | 0.39 |
| KM6.3  | 0.808 | 1.934 | 1.511 | 30.835 | 0.46 | 0.733 | 35.393 | 0.46 |
| KM12.7 | 1.416 | 1.448 | 0.821 | 35.665 | 0.55 | 0.912 | 51.925 | 1.292 |
| HM3.2  | 0.804 | 1.951 | 1.531 | 30.075 | 0.445 | 0.72  | 35.323 | 0.821 |
| HM6.3  | 1.319 | 1.632 | 0.6363| 45.712 | 0.661 | 1.081 | 57.872 | 1.325 |
| HM12.7 | 2.701 | 1.397 | 0.25  | 139.764| 1.737 | 2.903 | 142.449| 3.086 |

The Adj.R\(^2\) to fit RR, normal and lognormal distribution models were shown in Fig. 2. The results showed the comparison of the model fitting to RR distribution model (0.999≤Adj.R\(^2\)≤1), normal distribution model (0.744≤Adj.R\(^2\)≤0.968) and lognormal distribution model (0.742≤Adj.R\(^2\)≤0.942) for knife mill, and RR distribution model (0.998≤Adj.R\(^2\)≤0.999), normal distribution model(0.835≤Adj.R\(^2\)≤0.981) and lognormal distribution model (0.82≤Adj.R\(^2\)≤0.942) for hammer mill, respectively. The RR distribution model showed higher Adj.R\(^2\) for fitting the PSD data of all ground corn stover. The greater the value of Adj.R\(^2\) closes to 1, the more accurate the fit is. The results illustrated that the RR distribution was the best for fitting the PSD curves.

Figure 2. Adj. R\(^2\) of the RR, Normal, Lognormal distribution fit

3.2 Fitting characteristic
The characteristic particle size obtained by three distribution models and geometric mean diameter (d\(_{gw}\)) calculated by sieving method were shown in Fig. 3. For both mills, the geometric mean diameter and characteristic particle sizes were increased with the increase of the screen size. It can be observed in the Fig.3, the characteristic particle size fitted by three models was greater than the geometric mean diameter for both knife and hammer mills with different screens. This is due to the different particle shapes after grinding. During the sieving process, the slender large-sized particle passed through the siever to the next layer, thus the sieving process caused the particles accumulated to the underlying layer. But the statistics least squares method used in the model fitting homogenized the error and distributed the difference to each size fraction, thus the characteristic particle sizes calculated by the fitting distribution models were larger than the geometric mean diameter.

3.3 Grinding characteristics
Geometric mean diameter (d\(_{gw}\)) and geometric standard deviation (S\(_{log}\)) were shown in Fig.4(a). With an increase in screen size from 3.2 to 12.7 mm, geometric mean diameter of corn stover particle increased from 0.541 to 0.841 mm for knife mill, and from 0.621 to 1.764 mm for hammer mill, respectively. The knife mill has a smaller geometric mean diameter than the hammer mill with the same screen size. Corn stover grinded by the knife mill is finer than the hammer mill under the same conditions. Geometric
standard deviation of particles was similar for each screen size with minor variations, which only increased slightly with the increase of screen size for both mills. Higher geometric standard deviation also represented wider distribution of particles. From the above comparison, the RR distribution was the best-fit model among the three models, so the RR distribution ($m$) is used to analyse the differences between knife mill and hammer mill. With an increase in screen size from 3.2 to 12.7 mm, RR distribution parameter decreased from 2.113 to 1.448 for knife mill and from 1.951 to 1.397 for hammer mill, respectively (Fig. 4(b)). RR distribution parameter represented the uniformity of particles. Decreased value of RR distribution parameter represented less uniformity of particles. The knife mill has a higher value of RR distribution parameter than the hammer mill with the same screen size. Corn stover PSD grinded by the hammer mill had a wider span than the knife mill under the same conditions. Comparison of grinding characteristics of corn stover particles, the grinding performance of the knife mill is better than the hammer mill. This is due to the differences between mill structure and grinding principle. Knife mill had four rotating blades and one stationary blade to shear of corn stover for size reduction. Instead, hammer mill had a rotating drum with six swinging blades, it used swinging blades to impact, attrition, and compression for corn stover size reduction.

4. Conclusion

Biomass PSD is the most important factor in biomass energy conversion process. Many mathematical models were widely used to study the PSD. The three models, RR distribution, normal distribution and lognormal distribution, were evaluated in this study to describe the corn stover PSD. Results showed that the RR distribution model best described the corn stover PSD with the highest $\text{Adj. } R^2$ ($\text{Adj. } R^2 \geq 0.999$) among the three distribution models. The grinding characteristics, geometric mean diameter, geometric
standard deviation, and RR distribution parameter, were studied for knife mill and hammer mill, respectively. Within the same screen size, both particle size geometric mean diameter and geometric standard deviation for hammer mill were greater than knife mill. The average of geometric mean diameters was 0.541mm, 0.626mm, 0.814mm for knife mill and 0.621mm, 0.959mm, 1.764mm for hammer mill at screen size of 3.2mm, 6.3mm, and 12.7mm, respectively. The geometric standard deviation kept nearly constant for both knife mill and hammer mill. Within the same screen size, corn stover PSD with higher RR distribution parameter had narrow range for knife mill comparing to the hammer mill, hence, the grinding performance of the knife mill is better than the hammer mill for corn stover.

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