

Effect of reduced raw material moisture content on powder properties and energy requirements for size reduction

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Abstract: This study was conducted to evaluate the potential of single-stage chili milling (SSCM) as a substitute for the conventional multistage milling method to identify improvements that can be made to this process. This included reducing the moisture content of the chili to enhance the milling efficiency by increasing brittleness. Multiple stages were involved, including hammer mills and a pulverizer for chili milling. The initial moisture content of chili, which ranged from 12% to 13% w.b. during storage, was reduced to 3.5%-4% w.b. by allowing it to reach the equilibrium moisture content of chili at 20% relative humidity and a 37°C environment created using heat pump air dehumidifiers. SSCM trials were performed using a pulverizer. This study aimed to analyze the particle size distribution and its relationship with the energy consumption and flow indices, such as the Hausner ratio and compressibility index. The particle size distribution was described by parameters such as uniformity index, size range variation coefficient, mass relative span, skewness, kurtosis, size guide number, coefficient of uniformity, coefficient of gradation, and geometric standard deviation. The Rosin-Rammler (RR) model was proven to be a more suitable fit (R^2 of 0.954-0.967) than the Gaudin-Schumann (GS) model (R^2 of 0.725-0.808) when describing the particle size distribution across all samples. The energy consumption for grinding was analyzed using classical grinding laws, including Bond, Rittinger, and Kick's laws. Notably, the energy consumption of SSCM was significantly lower than that of conventional multistage chili milling. Additionally, the powder flowability of the SSCM method was comparatively lower than that of conventional multistage chili milling. However, the Hausner ratio and compressibility index of the SSCM were notably higher than those of the multistage ground powder.

Keywords: chili, particle size distribution, milling efficiency, Rosin-Rammler, Gaudin-Schumann, flowability, energy consumption

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1 Introduction

Chili pepper (*Capsicum annuum* L.) is an annual herb that belongs to the Solanaceae family. It is renowned for its spicy taste and has been incorporated into various cuisines worldwide. There are several documented health benefits and potential medicinal uses of peppers (Idrees et al., 2020). Particle size

reduction is referred to as a finer state of subdivision into smaller pieces of coarse particles or powder. This process is known as comminution or grinding. The reduction in the particle size of solids using mechanical means is known as milling (Bhatt and Agrawal, 2008).

Grinding is an energy-intensive process that

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involves the breakdown of hard substances (Henderson and Perry, 1976). The efficiency increases with a decrease in the moisture content of the material, as brittle materials consume less energy during grinding. However, materials with a high moisture content have greater ductility, leading to higher energy consumption. Several models, such as Rittinger, Kick, and Bond, have been developed to explain the energy consumption during the grinding of food and agricultural materials (Walde et al., 2002).

Multistage milling systems have become increasingly popular for commercial applications. Although these systems offer certain advantages, they also have certain drawbacks. According to Yap et al. (2022), the conventional multistage milling process can result in thermal damage, which may have deleterious effects on the volatile compounds found in chili peppers. The temperature at which these compounds are destroyed is typically associated with the roasting process. Roasting “Super-Hot” chilies at 120°C for 20–100 min can cause changes in the compounds present. Additionally, grinding chilies containing a significant amount of oil can release oil, leading to the loss of flavor, pungency, and volatile oil constituents. Furthermore, grinding is the most energy-intensive operation, with only a small portion of the energy applied to the material used to loosen the bonds between particles. The remaining 99% of the input energy was dissipated as heat, thereby increasing the temperature of the ground product. Energy consumption is relatively high in conventional multistage milling. According to previous studies by Liu et al. (2022) and Dhankhar and Hissar (2014), single-stage chili milling, which involves grinding chili peppers in a single step, is essential for preserving the flavor, aroma, and nutritional content of chili peppers. This method minimizes the exposure to heat and air, which can degrade these qualities. Additionally, single-stage milling is more cost-effective and environmentally friendly than multistage milling techniques because it reduces processing time and energy consumption.

Moreover, the particle shape and size distribution

were closely related to the hardness of the material. Food materials with high moisture contents exhibit irregular particle shapes owing to their brittle breakdown characteristics. Therefore, several mathematical models are available in the literature to describe the particle size distribution (PSD) across various materials and processes. Rosin-Rammler (RR) and Gaudin-Schumann (GS) are two of the most extensively used mathematical models (Brezani and Zelenak, 2010; Ulusoy and Igathinathane, 2016).

Singh et al. (2018) reported that the external morphological properties of each particle and the physical and chemical properties of the materials, including bulk density and flowability, influence the bulk properties of the powder. The flowability of the powders determines how well they flow under specific conditions. It can be assessed using various factors such as the Hausner ratio and Compressibility Index (CI). A good understanding of the flow characteristics and properties of spice powders is crucial for designing equipment and devices for handling, processing, transportation, storage, conveying, and packaging.

This study assessed the effectiveness of SSCM as a sustainable and cost-efficient alternative to conventional multistage chili processing. This enhances the brittleness of raw materials by reducing their moisture content, which not only decreases the environmental impact caused by the vaporization of volatile compounds during the milling process, but also minimizes the production cost. The ultimate goal was to determine the key elements necessary for the development of an industrial SSCM method that optimizes particle size distribution and flowability characteristics while minimizing energy consumption.

2 Materials and methods

A standard homogeneous bulk sample of commercially available dry chili (variety MI-2) was used. The chili had an average length of 8.23 cm, width of 1.25 cm, and thickness of 0.32 cm, with the moisture content (m.c.) being 11.98%±0.02% w.b. The objective of this study was to determine the possibility of single-stage chili milling (SSCM) to replace

conventional multistage milling at the industrial level. Specifically, this study investigated the particle size distribution pattern and its association with energy

consumption and flow indices. The experiments were conducted at Ruhunu Foods (Pvt) Ltd. in Kundasale, Sri Lanka.

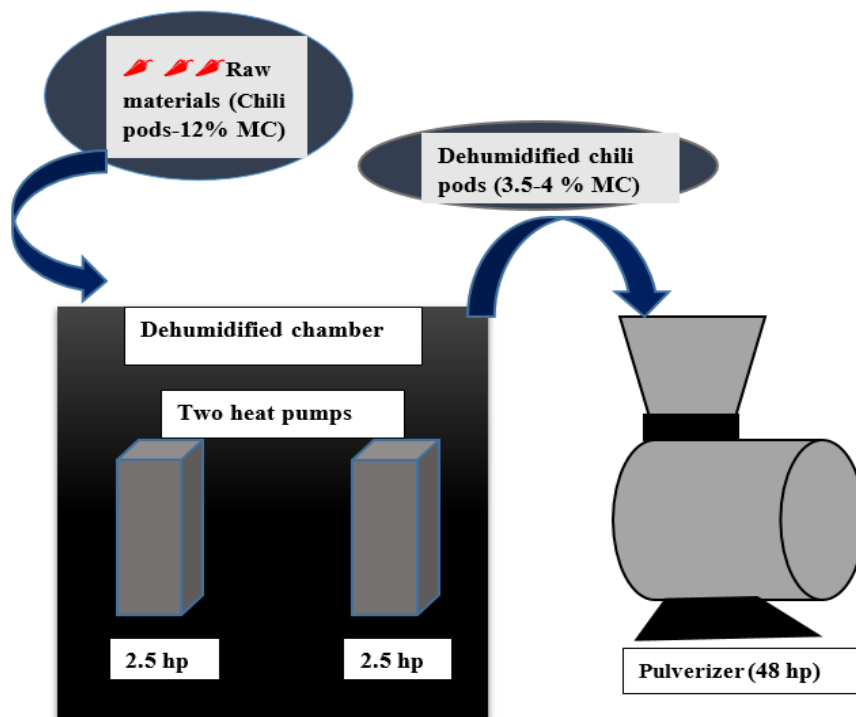


Figure 1 Schematic diagram of the experimental setup of the SSCM method

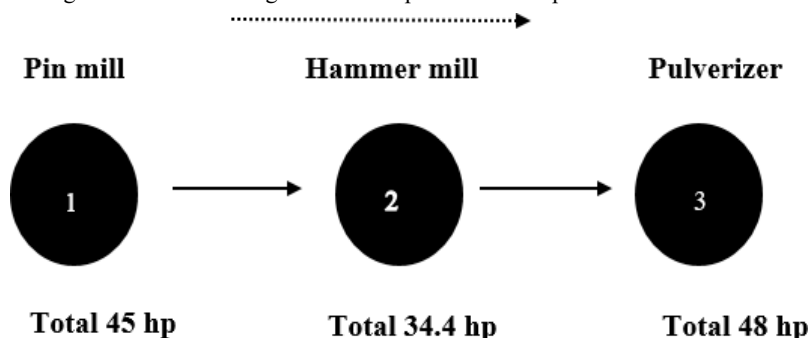


Figure 2 Schematic diagram of the conventional multistage chili milling method

As shown in Figure 1, dry chili pods were stored in a dehumidified chamber to reduce the moisture content until equilibrium moisture content was reached. According to Mehta and Singh (2006), the adsorption equilibrium moisture content for chili pods was approximately 4% at a relative humidity of 20% and temperature of 40°C using a modified Oswin model.

Based on this finding, a constant moisture content of 3.5%-4% w.b. was achieved for chili using two heat pumps at a relative humidity of 20% and a temperature of 37°C. The dehumidified chili pods were stored for several days to ensure equilibrium. The dehumidified chili pods were fed into a pin mill (Kaps Engineers, Model: PP-302, 831, GIDC, Makarpura, Vadodara

390010, India) to produce chili pieces with the desired initial diameter (1.62 mm). The experiments were carried out using a pulverizer with a classifying screen with a 1 mm opening. For each experimental run, a fixed quantity of chili (15 kg) was manually fed through the pulverizer (Kaps Engineers, Model: MP-31, 831, GIDC, Makarpura, Vadodara 390010, India) at a uniform feed rate of 0.25 kg s⁻¹, and the ground material was subjected to sieve analysis. The grinding time used for each experimental run was 1 min. The current consumption of the mill motor was used to calculate milling energy consumption.

Conventional chili powder was produced using a conventional multistage chili milling setup, as depicted

in Figure 2. This study obtained chili pods with a moisture content of $11.98\% \pm 0.02\% w.b.$ without dehumidification from the same chili variety. Initially, the chili pods were ground using a pin mill (Model: PP-302), followed by a hammer mill (Kaps Engineers, Model: HC:03, 831, GIDC, Makarpura, Vadodara 390010, India) and finally a pulverizer (Model: MP-31) to attain the desired fine powder consistency.

Table 1 Size parameters and formula for their determination

Parameter	Formula
Reference	
Fineness Modulus	$FM = \frac{\sum(\text{Cumulative retained } \%)}{100}$
Henderson and Perry (1976)	
Size guide number	$S_{gn} = D_{50}$
Hoffmeister (1982)	
Effective size	$Es = D_{10}$
Craig (2004)	
Uniformity index	$U_i = 100 \times \frac{D_5}{D_{95}}$
Hoffmeister (1982)	
Coefficient of uniformity	$C_u = \frac{D_{60}}{D_{10}}$
Craig (2004)	
Coefficient of curvature	$C_c = \frac{D_{30}^2}{D_{10} \cdot D_{60}}$
Craig (2004)	
Mass relative span	$M_{rs} = \frac{D_{90} - D_{10}}{D_{50}}$
Allais et al. (2006)	
Graphic mean	$G_m = \frac{D_{16} + D_{50} + D_{84}}{3}$
Folk and Ward (1957)	
Inclusive graphic skewness	$I_{gs} = \frac{(D_{16} + D_{84} - 2D_{50})}{2(D_{84} - D_{16})} + \frac{(D_5 + D_{95} - 2D_{50})}{2(D_{95} - D_5)}$
Folk and Ward (1957)	
Inclusive graphic standard deviation	$I_{gsd} = \frac{D_{84} - D_{16}}{4} + \frac{D_{95} - D_5}{6.6}$
Folk and Ward (1957)	
Graphic kurtosis	$G_k = \frac{D_{95} - D_5}{2.44(D_{75} - D_{25})}$
Folk and Ward (1957)	

2.1 Sieve analysis

A laboratory sieve shaker (Endecotts, Model: BS410-1:2000) was used to separate the ground chili powder into different particle sizes. Typically, the sieve mesh sizes were 75-2000 μm , with the smallest and largest mesh screens positioned at the bottom and top of the sieve, respectively. On the top sieve, 250 g of chili powder was added and vigorously shaken for approximately 20 min. The mass percentage of each sample was calculated by weighing the particles that were retained on each screen. Particles that passed through the fine screen were collected in a pan at the bottom of the stack. The same procedure was used to

assess the intermediate particle sizes of the chili pieces fed into the pulverizer.

2.2 Determination of size parameters

The particle size is a crucial characteristic of particulate materials. Common size parameters (Table 1) include D values, which are related to the cumulative distribution functions. These functions offer insights into the particle size distributions across various size ranges, such as undersized and oversized D-values. The coefficient of uniformity and mass relative span are essential parameters for characterizing the particle size distribution. The coefficient of uniformity measures the degree of variation in particle size, whereas the span value reflects the spread or width of the distribution. A higher span value indicated a broader distribution and lower consistency of particle size, whereas a lower value indicated a narrower distribution and higher consistency. These parameters are vital for assessing the uniformity of the particle size distribution and can be used to evaluate the consistency of the particle sizes within a sample. The coefficient of curvature, which gauges the uniformity of the particle size distribution, is crucial for its evaluation. A value between 1 and 3 for the coefficient of curvature indicates a well-graded distribution of particle sizes, suggesting a balanced distribution (Bitra et al., 2009; Craig, 2004). Skewness, another significant parameter, measures the asymmetry of a distribution around its peak. Higher positive values indicated increased asymmetry for larger particle sizes. Kurtosis quantifies the deviation from a normal distribution. A kurtosis value of 1.00 represents a perfect Gaussian distribution, while lower values suggest flatter distributions with a greater number of outliers, and higher values imply sharper-peaked distributions with fewer outliers (Folk and Ward, 1957).

2.3 Mathematical models for particle size distribution

This research relied on the Rosin-Rammler (RR) and Gaudin-Schuhmann (GS) distribution functions, which are commonly used to assess powder size distribution data. According to Shashidhar et al. (2013)

and Vítěz et al. (2011), these models are highly regarded for their versatility and aptitude for accurately depicting particle size distributions for various materials and conditions. The RR model is often preferred because of its strong correlation with experimental data. Vítěz et al. (2011) reported the GS model has demonstrated superior separation of particle sizes for industrial applications.

2.3.1 Estimation of Rosin-Rammler (RR) model constants

The Rosin–Rammler distribution function is one of the most extensively used mathematical models. The following equation can describe the Rosin-Rammler particle size distribution:

$$R = 100 \cdot e^{-\left(\frac{d}{d_m}\right)^n} \quad (1)$$

Where,

R represents the cumulative percentage of retained material, d is the sieve size (μm) or particle size;

d_m is the size parameter (μm), and n is the distribution parameter.

The following is the result of using the above equation: $\ln\left(\ln\frac{100}{R}\right) = n \cdot \ln d - n \cdot \ln d_m$ (2)

Therefore, the plot of $\ln(\ln 100/R)$ versus $\ln(d)$ is a straight line. Thus, it was possible to determine the values of d_m and n . The Rosin-Rammler model is generally applicable to a wide range of comminution processes, including crushing and milling operations as well as the breaking up of liquid sheets during atomization. This broad applicability is because of the model's ability to describe skewed distributions (Vítěz et al., 2011; Ulusoy and Igathinathane, 2016).

2.3.2 Estimation of Gaudin Schuhmann (GS) model constants

The following equation can describe the GS model particle size distribution:

$$D = 100 \left(\frac{d}{d_{max}}\right)^m \quad (3)$$

In this equation, D refers to the cumulative percentage of the passing material, d refers to the particle size or sieve size (μm), d_{max} refers to the maximum particle size (μm), which is the size distribution within the overall size spectrum, and m

refers to the distribution modulus, which indicates the degree to which the size distribution is broad. Using the above equation can be determined as follows:

$$\ln D = \ln(100) + m \cdot \ln(d) - m \cdot \ln(d_{max}) \quad (4)$$

Therefore, plotting $\ln(D)$ versus $\ln(d)$ frequently yields straight lines across a wide range of sizes, particularly for finer sizes. The slope of this straight line corresponds to the distribution modulus (m) and the size at which the extrapolated line intersects the cumulative undersize by 100% represents the size modulus (d_{max}) (Fuerstenau and Han, 2003; Vítěz et al., 2011).

2.4 Flow characteristics of chili powders

The properties were evaluated to assess the flow behavior of ground chili powders.

2.4.1 Bulk and tapped densities of chili powder

The bulk and tapped densities of the powders were obtained using a graduated measuring cylinder with a volume of 100 ml. To ensure accuracy, the chili powder was carefully poured into a cylinder at a fixed level using a regular funnel. The upper layer was then flattened using an iron strip and the volume and weight of the powder in the cylinder were measured and recorded. The bulk density of the chili powder was calculated using Equation 5.

$$\rho_b = \frac{m_b}{V_b} \quad (5)$$

In this equation, ρ_b represents the bulk density (kg m^{-3}), whereas m_b and V_b denote the mass of the powder (kg) and its corresponding volume (m^3), respectively. The tapped density was determined using a cylinder with a volume of 100 ml, into which the powder was carefully poured to a fixed level. Then, the cylinder was manually tapped vertically. Tapping was discontinued when the height of the powder in the cylinder ceased to change with further tapping. The tapped density of the chili powder was calculated using Equation 6.

$$\rho_t = \frac{m_t}{V_t} \quad (6)$$

The density of the powder, denoted by ρ_t (kg m^{-3}), was determined by the ratio of the tapped mass (m_t , kg) to its corresponding tapped volume (V_t , m^3).

2.4.2 Hausner ratio

The Hausner ratio is the ratio of the tapped density (kg m^{-3}) of the powder to the bulk density (kg m^{-3}) of chili powder. The Hausner ratio was obtained as follows:

$$H_r = \frac{\rho_t}{\rho_b} \quad (7)$$

Where,

H_r represents the Hausner number;

ρ_b and ρ_t are the same variables as mentioned above.

The Hausner ratio measures the flowability of powder in a loosely packed state.

2.4.3 Compressibility Index

The compressibility index measures the degree to which a powder can be compressed. The compressibility index indirectly measures material properties, such as bulk density, size, shape, surface area, moisture content, and cohesiveness. This can be obtained as follows.

$$CI = 100 \times \left(\frac{\rho_t - \rho_b}{\rho_t} \right) \quad (8)$$

CI is the compressibility index, and ρ_b and ρ_t are the same variables, as mentioned previously. A variation of these methods involves measuring the rate of consolidation rather than, or the change in volume that occurs during tapping (Santomaso et al., 2003; Singh et al., 2018; De Jong et al., 1999).

2.5 Energy requirements for the size reduction

Various parameters were evaluated for the size reduction process of SSCM and conventional multistage chili milling methods based on energy requirements.

2.5.1 Final weight mean diameter (L_2)

Based on sieve analysis of the powder, the final weight mean diameter (L_2) was determined as follows:

$$L_2 = \int_0^{1.0} D_p \cdot \Phi(d) \quad (9)$$

Where,

D_p represents the average aperture size of the sieve;

$\Phi(d)$ represents the mass fraction of particles with a diameter of D_p (Shashidhar et al., 2013).

Equation 9 was also used to calculate L_1 (the mean diameter of the feed material).

2.5.2 Size reduction ratio

$$S_R = \frac{L_1}{L_2} \quad (10)$$

It is important to understand the reduction ratio when performing processes such as grinding, cutting, or milling so that the energy consumption can be optimized (Kumar et al., 2022).

2.5.3 Laws for comminution energy

Kick, Rittinger, and Bond's laws are empirical relationships that describe the energy required for particle size reduction in comminution processes. Therefore, Kick's, Rittinger's, and Bond's Work index constants were calculated as follows:

Kick's law:

$$E = K_k \ln \left[\frac{L_1}{L_2} \right] \quad (2)$$

Rittinger's law:

$$E = K_r \left[\frac{1}{L_2} - \frac{1}{L_1} \right] \quad (12)$$

Bond's law:

$$E = K_b \left[\frac{1}{\sqrt{L_2}} - \frac{1}{\sqrt{L_1}} \right] \quad (13)$$

Bond's work index:

$$W_{ind} = \frac{K_b}{0.3162} \quad (14)$$

Assuming that E is the energy requirement for grinding; L_1 and L_2 are the mean diameters of the initial and final ground particle sizes, respectively; and K_b , K_k , and K_r are Bond's, Kick's, and Rittinger's constants, respectively (McCabe et al., 1993).

Kick's law suggests that the energy required for comminution is proportional to the ratio of the initial size to the final size, whereas Rittinger's law posits that the energy required is proportional to the new surface area created. On the other hand, Bond's law is based on the work required to reduce a material from a theoretically infinite size to a size that 80% passes a 100 μm screen (Rozalli et al., 2015). The Bond Work Index (BWI/W_{ind}), a vital component of the milling process, indicates the grindability of the materials and is used to estimate the power required for grinding

operations (Deniz and Ozdag, 2003; Rizk, 2020). Predicting the energy consumption during the size reduction process is essential for selecting comminution equipment and mineral processing (Aras et al., 2019; Nikolić and Trumić, 2021).

2.5.4 Specific energy consumption

Specific energy is the amount of energy required to grind a unit mass of the feed material. The power requirements, particle size, and surface area are affected by several factors such as the initial size, material type, particle strength, particle shape, hardness, smoothness, brittleness, stickiness, moisture content, type of grinding device, and mechanical parameters that are fixed during grinding (Meghwal and Goswami, 2013). This can be expressed in kJ kg^{-1} based on the specific energy consumed (S_E) in Equation 15.

$$S_E = \left(\frac{P_C}{M} \right) \quad (15)$$

Where,

P_C is the total amount of power consumed in grinding a given mass of chili, expressed in kJ;

M is the mass of chili, expressed in kg.

2.6 Statistical analysis

The experiments were conducted in triplicate. All data obtained from the experiments were statistically analyzed using the Statistical Package for the Social Sciences (SPSS) software (IBM Corporation, USA, Version 20.0). Variations in mean values were assessed for significance using ANOVA (Analysis of Variance) in conjunction with the Duncan test. Each level of significance (a-b) was assigned significant values, with significance set at $p < 0.05$.

3 Results and discussion

3.1 Particle size distributions and size parameters

The particle size distribution of the experimental runs was determined by performing sieve analysis and plotting the results as particle size against the cumulative passing weight percentage. Table 2 records cutoff diameters (D_5 , D_{10} , D_{16} , D_{25} , D_{30} , D_{50} , D_{60} , D_{75} , D_{84} , D_{90} , and D_{95}) calculated for each run. Table 1 lists the various size parameters describing the particle size

distribution characteristics of the samples, as shown in Figure 3. As shown in Figure 3, the SSCM method displayed lower values for key parameters, such as the size guide number (0.14), uniformity index (3.26), and effective size (0.03), than the conventional multistage chili milling method (0.21, 10.63, and 0.09, respectively). Additionally, the SSCM method exhibited lower values for other metrics, including the graphic mean (0.16), inclusive graphic standard deviation (0.13), and fineness modulus (1.44) than the conventional multistage milling method (0.24, 0.17, and 2.17, respectively). However, it should be noted that the mass relative span of the SSCM method was higher than that of the conventional multistage chili milling method. SSCM method produces a broader particle size distribution compared to conventional multistage chili milling, as evidenced by a higher mass relative span. A higher mass relative span signifies greater heterogeneity in particle sizes, implying that the SSCM process generates a wider range of particle dimensions.

Furthermore, a lower coefficient of curvature was observed for the SSCM method than for the conventional multistage chili milling method, suggesting that a more uniform particle size distribution was achieved. According to Craig (2004), in the results of the present study, the coefficient of uniformity for the SSCM method was observed to be greater than 6, suggesting a densely graded material with a wider range of particle sizes, whereas the coefficient of uniformity for the conventional multistage chili milling method was found to be less than 4, indicating a uniformly graded material with a narrower size range. Therefore, based on the coefficient of uniformity and curvature, it can be concluded that the SSCM method led to the production of a more densely graded material than the conventional multistage chili milling method. According to Folk and Ward (1957), based on the results of the present research, it can be inferred that positive skewness was exhibited in the particle size distributions of both SSCM and conventional multistage chili milling methods, with skewness values

surpassing +0.30. Additionally, flatter distributions with a larger number of outliers were suggested by the lower kurtosis values (0.03 for the SSCM method and 0.06 for the conventional multistage chili milling methods). These results indicated that the particle size

distribution parameters calculated using the SSCM method were significantly different from those calculated using the conventional multistage chili milling method.

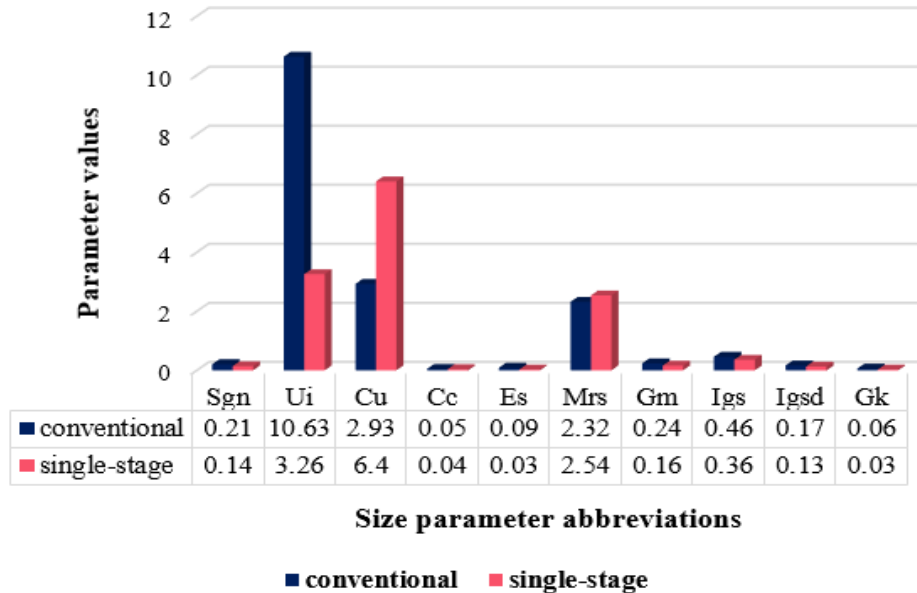


Figure 3 Size parameters of particle distribution

Table 2 Various cut-off diameters (mm) to represent the PSD of ground chili

Cumulative passing weight (%)	Cut-off diameters (mm)	
	Conventional multistage chili milling method	SSCM method
D ₅	0.08 ^a ±0.0011	0.01 ^b ±0.0002
D ₁₀	0.09 ^a ±0.0009	0.03 ^b ±0.0001
D ₁₆	0.10 ^a ±0.0005	0.04 ^b ±0.0002
D ₂₅	0.12 ^a ±0.0005	0.07 ^b ±0.0003
D ₃₀	0.13 ^a ±0.0008	0.08 ^b ±0.0003
D ₅₀	0.21 ^a ±0.0022	0.14 ^b ±0.0008
D ₆₀	0.25 ^a ±0.0023	0.17 ^b ±0.0011
D ₇₅	0.36 ^a ±0.0011	0.24 ^b ±0.0005
D ₈₄	0.42 ^a ±0.0020	0.32 ^b ±0.0001
D ₉₀	0.56 ^a ±0.0063	0.37 ^b ±0.0010
D ₉₅	0.71 ^a ±0.0031	0.42 ^b ±0.0017

Note: Values represented as mean ± standard deviation (N = 3)

Different superscript letters differ significantly according to Duncan’s multiple range test ($p \leq 0.05$)

3.2 Mathematical models for particle size distribution

Table 3 Comparison of the RR and GS models’ parameters

Milling method	RR model			GS model		
	$d_m (\mu m)$	n	R ²	$d_{max} (\mu m)$	m	R ²
Conventional multistage	256.2	1.15	0.967	1339	0.34	0.808
SSCM	156.3	0.88	0.954	1211	0.20	0.725

Based on the results, the RR model emerged as the most effective model for chili milling. Table 3 shows the parameters of both the RR and GS models, as well

as the correlation coefficients for the particle size distributions of the chili powders determined by both methods.

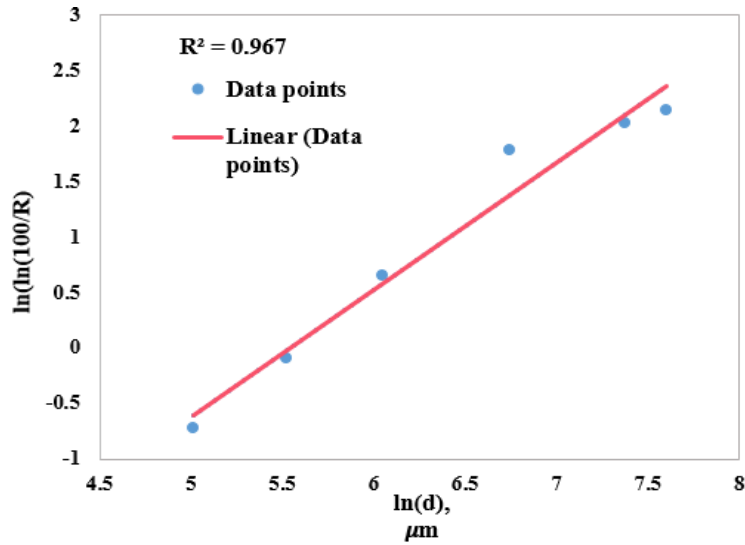


Figure 4 RR model regressed particle size distribution of the conventional multistage chili milling method

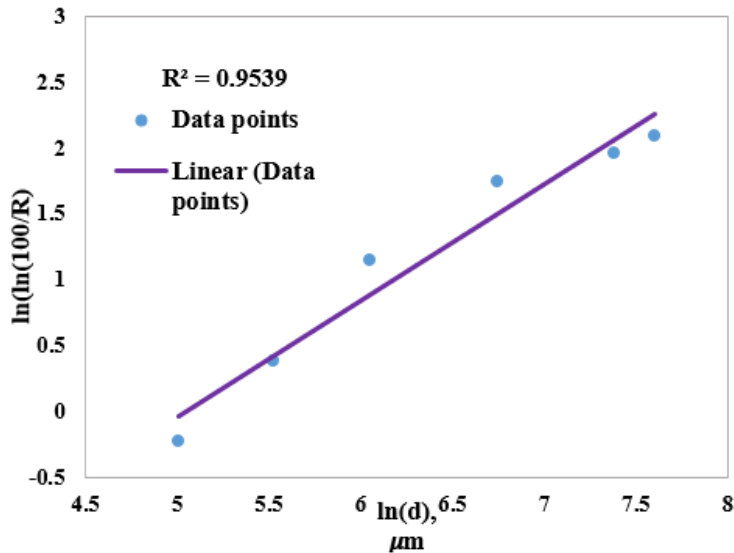


Figure 5 RR model regressed particle size distribution of the SSCM method

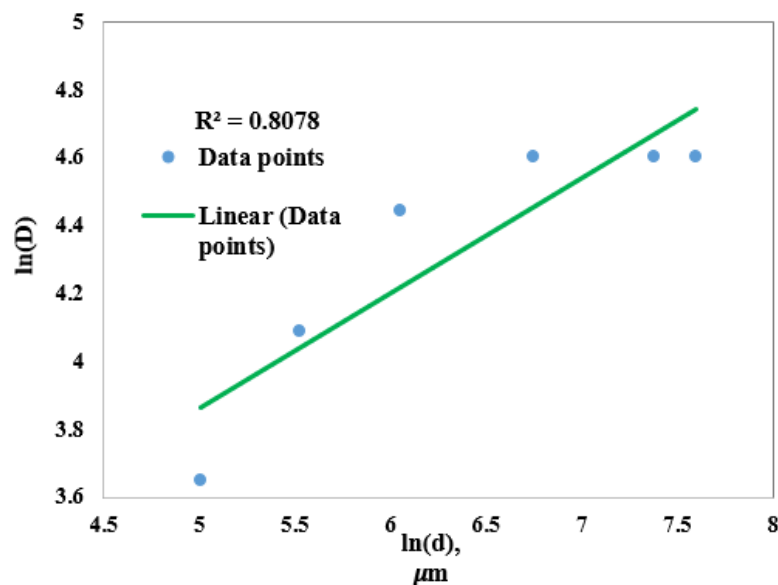


Figure 6 GS model regressed particle size distribution of the conventional multistage chili milling method

Figures 4 and 5 show the regression of the experimental particle size distribution fitted to the RR model, whereas Figures 6 and 7 show the regression of the experimental particle size distribution fitted to the GS model for both milling methods. Therefore, RR regressed very well for both the SSCM method and the conventional multistage chili milling method (R^2 of 0.954–0.967) compared to GS (R^2 of 0.725–0.808). As a result of these experiments, the Rosin-Rammler distribution parameters (0.88–1.15) were comparatively higher than the GS model (0.20–1.34). Based on experimental turmeric grinding using conventional and cryogenic grinding methods, Manohar and Sridhar (2001) found that the RR equation best fitted the experiment. Turmeric's RR distribution parameter was reported to be 2.60, whereas of that pepper was reported to be 1.45–2.29.

For sources such as Tangirala et al. (2014) and Shashidhar et al. (2013), the RR model demonstrated significant promise for evaluating the particle size distribution of spices. Its successful application in determining the optimal milling technique for cinnamon, coriander, and turmeric, along with its high correlation coefficient for the particle size distribution in grinding coriander seeds, supports this claim. However, the applicability of this conclusion to all species and grinding conditions warrants further validation. Notably, Vítěz et al. (2011) reveals that the Gates-Gaudin-Schuhmann (GGS) model outperformed the Rosin-Rammler (RR) model in separating particle sizes for waste sand from a wastewater treatment plant, suggesting a more accurate assessment of particle sizes for industrial purposes.

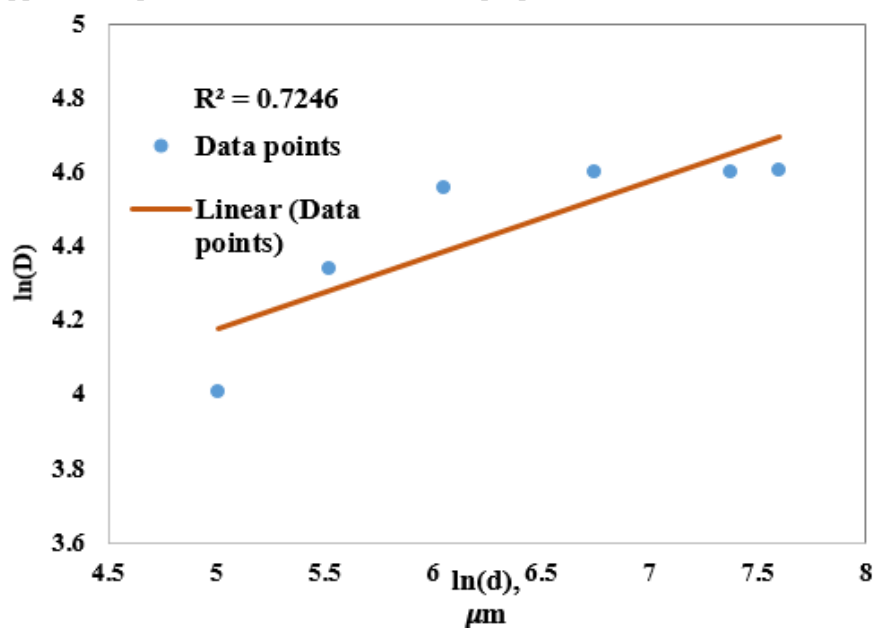


Figure 7 GS model regressed particle size distribution of the SSCM method

3.3 Flowability

The processing conditions significantly affected the flowability of the chili powder, as demonstrated by the various parameters. As shown in Table 4, the flowability of the chili powder was significantly affected by the processing conditions, as evidenced by the various parameters. The bulk density ($408.21 \pm 1.01 \text{ kg m}^{-3}$) and tapped density ($471.29 \pm 0.97 \text{ kg m}^{-3}$) of chili powder processed using an improved SSCM method were found to be lower compared to those of the conventional multistage milling method (bulk

density $468.70 \pm 0.76 \text{ kg m}^{-3}$ and tapped density $538.74 \pm 0.71 \text{ kg m}^{-3}$). However, it should be noted that the Hausner ratio and compressibility index of the ground chili powder obtained using the SSCM method were noticeably higher than those of the conventional multistage ground chili powder. Carr (1965) reported, that the Hausner ratio was generally found to fall within the range of 1.12–1.18, while the complexity index ranged between 11–15, indicating free-flow characteristics. As a result, both powders exhibited free-flow properties.

Table 4 Flowability of ground chili powders

Milling method	Bulk density (ρ_b) (kg m^{-3})	Tapped density (ρ_t) (kg m^{-3})	Hausner ratio (Hr)	Compressibility Index (CI)
SSCM	408.21±1.01 ^b	471.29±0.97 ^b	1.15±0.002 ^a	13.39±0.19 ^a
Conventional multistage	468.70±0.76 ^a	538.74±0.71 ^a	1.14±0.0003 ^b	13.00±0.03 ^b

Note: Values represented as mean ± standard deviation (N = 3)

Different superscript letters differ significantly according to Duncan's multiple range test ($p \leq 0.05$)

Recent research, including a study by Suhag et al. (2024), suggests that the cohesiveness of chili pods can be improved by decreasing their particle size. This improvement is attributed to the increased brittleness of the chili pods, which leads to a reduction in particle size or an increase in specific surface area, facilitating interparticle bonding and interactions, and enhancing cohesiveness. The results of this study were consistent with those of conventional studies on powder materials, which showed that flowability parameters such as the Hausner ratio and compressibility index were affected by particle size. These findings indicated that the SSCM method produced finer ground powder than the conventional multistage chili milling method.

According to Singh et al. (2018), cryo-ground powder has a smoother, smaller, and more regular particle size than ambient ground powder. Specifically, the bulk density of the cryoground powder was 414 kg m^{-3} , whereas that of the ambient ground powder was

483 kg m^{-3} . Similarly, the tapped density of the cryo-ground powder was 480 kg m^{-3} , whereas that of the ambient ground powder was 556 kg m^{-3} . It should be noted that the Hausner ratio and compressibility index of ambient ground chili powder were significantly lower than those of cryoground powder.

3.4 Energy requirements for the size reduction

According to the basic principles of comminution, achieving higher size reduction ratios signifies a more efficient process of reducing particle size (Galecki et al., 2013). In this study, a noticeable distinction was found between the size reduction ratios achieved by the SSCM method (13.5) and the conventional multistage chili milling method (8.53). The greater reduction ratio obtained with SSCM suggests more effective particle fragmentation within a single system, indicating enhanced grinding performance and better energy utilization. While both methods were capable of delivering satisfactory grinding outcomes, the SSCM method proved to be more efficient in producing finer particle sizes.

Table 5 Comparison of the energy requirements for size reduction

Milling method	Size reduction ratio	Measured energy (kJ kg^{-1})	Kick's constant (kJ kg^{-1})	Rittinger's constant (kJ kg^{-1})	Bond's constant (kJ kg^{-1})	BWI (kWh t^{-1})	Specific energy (kJ kg^{-1})
SSCM	13.5	266	102.30	34.47	31.75	8.82	88.65
Conventional multistage	8.53	1116	519.86	240.17	290.28	255	611

As illustrated in Table 5, there was a significant difference in energy consumption between the two milling techniques. The SSCM method required considerably less energy (266 kJ kg^{-1}) compared to the conventional multistage chili milling method (1116 kJ kg^{-1}). This substantial difference can be attributed to the multistage nature of the conventional milling process, which involves repeated grinding, increased material handling, and cumulative energy losses at each stage. Conversely, the SSCM system seems to minimize unnecessary energy dissipation, resulting in

a lower overall energy requirement. Previous research has indicated that grinding energy increases with higher moisture content and greater resistance to particle fracture (Djantou et al., 2007), whereas materials with lower moisture content demand less energy for size reduction (Lee et al., 2013). These findings corroborate the observed lower energy requirement of the SSCM method.

Additional proof of enhanced efficiency is demonstrated by the comminution constants derived from Kick's, Rittinger's, and Bond's laws. The SSCM

method showed lower values for Kick's constant ($102.30 \text{ kJ kg}^{-1}$), Rittinger's constant (34.47 kJ kg^{-1}), and Bond's constant (31.75 kJ kg^{-1}) when compared to the conventional multistage milling approach. These reduced constants suggest a decrease in energy needed for particle size reduction during coarse, intermediate, and fine grinding stages. In contrast, the higher constants found in the conventional method indicate greater resistance to size reduction and less efficient energy transfer during milling.

The Bond Work Index (BWI) further underscores the superior performance of the SSCM method. The BWI value for SSCM (8.82 kWh t^{-1}) was significantly lower than that of the conventional multistage chili milling method (255 kWh t^{-1}), signifying better grindability and reduced energy requirements. Although BWI values can vary greatly based on material characteristics, reported values for spices and cereals are typically much higher, such as pepper ($4610\text{--}42220 \text{ kWh t}^{-1}$), wheat ($1580\text{--}2050 \text{ kWh t}^{-1}$), and cumin ($40\text{--}80 \text{ kWh t}^{-1}$) (Murthy, 2001; Goswami and Singh, 2003). The relatively low BWI for SSCM indicates that this milling configuration greatly improves grinding efficiency.

The trend is further confirmed by specific energy consumption. The SSCM method required only 88.65 kJ kg^{-1} , which is significantly less than the specific energy needed by the conventional multistage milling process (611 kJ kg^{-1}). Lower specific energy values mean that less energy is used per unit mass to achieve the desired particle size. Similar reductions in specific energy have been observed for other agricultural materials under optimized milling conditions (Bitra et al., 2009). Overall, the lower size reduction constants, BWI, and specific energy consumption demonstrate that the SSCM method is a more energy-efficient and economically advantageous alternative to conventional multistage chili milling.

4 Conclusion

It can be concluded that this research study significantly contributed to the field of chili processing by providing substantial advancements. The results

revealed that the SSCM method was a feasible alternative to conventional multistage chili milling. By reducing the moisture content of chili pods, this method increased their brittleness, thereby enhancing the efficiency of the milling process. Analysis of the particle size distribution patterns revealed the relationship between the energy consumption and flow indices. The Rosin-Rammler model was more suitable than the Gaudin-Schumann model for describing the particle size distribution across all samples. Furthermore, the study demonstrated that the energy consumption associated with size reduction of the SSCM method was significantly lower than that of conventional multistage chili milling, indicating the potential for more energy-efficient practices. Analysis of the powder flowability revealed that the powder flowability of the SSCM method was comparatively lower than that of the conventional multistage chili milling. The Hausner ratio and compressibility index of the single-stage ground chili powder were significantly higher. The research entailed employing "dehumidification" with heat pumps to diminish the moisture content of the raw material. Further industrial feasibility should be studied for powdered products using the SSCM method.

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Nomenclature

FM	Fineness Modulus
I_{gsd}	Inclusive graphic standard deviation
G_k	Graphic kurtosis
C_c	Coefficient of curvature
M_{rs}	Mass relative span
G_m	Graphic mean
I_{gs}	Inclusive graphic skewness
S_{gn}	Size guide number
U_i	Uniformity Index
C_u	Coefficient of uniformity
$D_5, D_{10}, D_{16}, D_{25}, D_{30}, D_{50}, D_{60}, D_{75}, D_{84}$	Particle size corresponding
D_{90}, D_{95}	to 5%, 10%, 16%, 25%, 30%, 50%, 75%, 84%, 90% and 95% cumulative undersize mass
d	Particle size
R	Cumulative percentage of the retained material
d_m	Size parameter of RR model
n	Distribution parameter of RR model
D	Cumulative percentage of the passing material
d_{max}	Size modulus of GS model
m	Distribution modulus of GS model
ρ_b	Bulk density
m_b	Mass of the powder
V_b	Volume of the powder
ρ_t	Tapped density
m_t	Tapped mass of the powder
V_t	Tapped volume of the powder
H_f	Hausner ratio
CI	Compressibility index
L_1	Mean diameter/particle size of feed material
L_2	Mean diameter/ particle size of the final product
D_p	Average aperture sizes of sieve
$d\phi$	Mass fraction of particles
S_R	Size reduction ratio
E	Energy
K_k	Kick's constant
K_r	Rittinger's constant
K_b	Bond's constant
W_{ind}	Bond's work index
S_E	Specific energy
