MODELING OF SIZE REDUCTION, PARTICLE SIZE ANALYSIS AND FLOW CHARACTERISATION OF SPICE POWDERS GROUND IN HAMMER AND PIN MILLS

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Abstract

Comparative study using Rosin-Rammler-Sperling-Bennet (RRSB) and Rosin-Rammler model parameters, including particle size analysis and flow characterization helps in identifying whether hammer mill or pin mill is suitable for grinding three selected spices, namely, cinnamon, coriander and turmeric. Model parameters like degree of uniformity in size and statistical average diameter of ground products, mean sizes of ground particles, Bond's work index, specific energy consumption for grinding, and flow characteristics indicate cinnamon and coriander are suitable for grinding with hammer mill while turmeric is suitable for grinding with pin mill.

Keywords: *Rosin-Rammler-Sperling-Bennet model, coriander, cinnamon, turmeric, degree of uniformity, statistical average diameter, Bond's work index, specific energy.*

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1. INTRODUCTION

In recent years, particularly in food and pharmaceutical industry, product quality criteria have become more and more draconian, imposing specifications involving finer particles and closer control on the mean particle size, or the width and cut-off of the particle size distribution [1]. The theory of grinding has mainly been developed in the mineral industry as a response to need for maximizing production capacity and minimizing energy use for low value added products [2]. There is a paucity of literature in grinding of food materials. This is partly due to the fact that products from natural sources are more variable, making investigation difficult to generalize [1].

Grinding and size reduction of spices have been undertaken mainly for the following reasons: (a) to reduce transportation cost by minimizing volume of spices to be transported; (b) to have easy bioavailability of medicinal and nutritional contents through spice powders; (c) to add powders easily to various food and medicinal formulations; (d) to augment packing and storage of powdered spices easily.

Power requirements in terms of size of comminuted particles and increase of surface areas are dependent on initial size, shape and strength of particle; type of mill used for size reduction and the operating parameters fixed for running the mill [3]. The energy laws in practice have not been proved to be very successful, most likely because, only a very small amount of the total energy used in milling devices is actually used for breakage of particles. A great deal of energy input in to a mill is used to create noise and heat as well as simply moving the materials around the devices. Mill efficiency can be judged in terms of energy input into the device as compared to the particle size achieved for a given material [4]. Thus only bonds work index is considered for the present study.

Flowability of Powder is a property with which a powder will flow under a specific set of conditions [5]. It can be characterized with the help of many factors such as flow index, Hausner ratio, Carr index (*CI*), Compressibility index (*CPI*) and angle of repose etc. Knowledge of flow characteristics and properties of spice powders are essential for designing equipment's and devices for its handling, processing, transporting, storing, conveying and packaging purposes.

The aim of the present paper was to study how particle size distribution, energy consumption during grinding of spice and flow characteristics of spice powders vary when they are ground with the help of pin and hammer mills. Particle size distribution of the ground spice was modeled using Rosin-Rammler-Sperling-Bennet (*RRSB*) and Rosin-Rammler (*RR*) equations [3] to find out the degree of uniformity (n) and statistical average diameter (M). The models, thus, developed could be used to predict the degree of uniformity and statistical average diameter of ground spice powders obtained from pin and hammer mills.

2. MATERIAL AND METHODS

Different materials such as turmeric, cinnamon, and coriander were taken in the present study. The methods used to determine different parameters have been described in details in this section.

2.1 Sample Preparation

Spices, namely Turmeric (*Curcuma longa*) rhizome (var. IISR Alleppey Supreme), were procured from the Indian Institute of Spice Research (IISR), Kozhikode, India; Cinnamon (*Cinnamomumzeylanicum*) bark (var. Nityashree) from IISR, Calicut, India; Coriander (*Coriandrumsativum*) seed (RCR-4) from the National Research Centre for Seed Spices, Ajmer, India; and considered for grinding. Initial moisture content (M.C.) of the samples was determined by Entrainment method [6]. Spices were dried at 50 °C in a hot air dryer (Riviera Glass Pvt. Ltd., Mumbai, India.) and final moisture content of the sample was set to 10.2±0.3 (%, db.). The initial dimensions of the cinnamon, coriander and turmeric spices before grinding were determined using a dial caliper (Mitutoyo Corporation – D30TN) having measuring range of 0 – 300 mm with a graduation of 0.02 mm and external and internal errors of ±0.010 and ±0.020 mm respectively. The dimensions of cinnamon, coriander and turmeric were 71.81 mm (L) × 9.45 mm (B) × 1.00 mm (T); 4.09 mm (L) × 3.33 mm (B) × 3.08 mm (T); and 40.57 mm (L) × 9.77 mm (B) × 5.47 mm (T) respectively.

2.2 Grinding Procedure

Spices, namely, Turmeric, Cinnamon and Coriander were ground in an impact type of hammer mill and in a pin mill. Spice samples which were ground in pin mill were designated as PT_u– turmeric ground in pin mill; PC_i – cinnamon ground in pin mill; and PC_o – coriander ground in pin mill. Similarly spice samples ground in hammer mill were designated as HT_u – turmeric ground in hammer mill; HC_i – cinnamon ground in hammer mill; HC_o – coriander ground in hammer mill.

The hammer mill was fitted with 4 fixed-type of hammers and the grinding chamber was housed with a control screen for controlling the degree of fineness of grinding. The material was crushed and pulverized between the hammers and the casing and remained in the mill until it was fine enough to pass through a screen which formed the bottom of the casing. Both brittle and fibrous materials could be handled in hammer mills, though with fibrous material, projecting sections on the casing may be used to give a cutting action [7]. The hammer mill used in the study is shown in Fig. 1, which was fabricated indigenously from Tailibali manufacturers, Kolkata based on design parameters supplied by IIT Kharagpur.

The pin mill consisted of two co-axially mounted plates, one was rotating and the other was stationary. Pins were fixed to each plate in five circular rows (two in fixed plate and 3 in movable plate) with increasing number of pins from inner to outer row (8, 13, 16, 19, and 24 respectively) as shown in Fig. 2. (a). Pin mill have a higher energy input than that for hammer mill and can generally grind softer materials to a finer particle size than that of hammer mill, while hammer mill performs better on hard or coarse materials [4]. The pin mill used in the study is shown in Fig. 2. (b), which was fabricated indigenously from Tailibali manufacturers, Kolkata based on design parameters supplied by IIT Kharagpur.

The pin mill was run at 1300 rpm with the help of DC motor controller having specifications of 2 h.p., 220 V, 8 amps (make, Creative Controls, Mumbai, India). Experimental runs were carried out with classifying screen (U.S. 45 mesh) with an opening of 354 microns. For each experimental run, a known fixed quantity of spice (200 g) was fed to the mill at a uniform feed rate of 2.5 g s^{-1}, and the ground material was subjected to sieve analysis. The grinding time for each experimental run was 10 minutes. Energy consumed for each run was noted down from an energy meter (Bentec electrical and electronics, Pvt. Ltd., Kolkata, India) connected to the comminuting mill. The meter directly provided energy values for grinding in kWh units with an error of ±0.1 kWh.

2.3 Sieve Analysis

Ground spice powder obtained as per the procedure described above was separated into different particle size fractions using a set of sieves in a laboratory sieve shaker (FRITSCH, Analysette 3 spartan, pulverisette, Germany) with 3 mm amplitude. The set of standard sieves (75–500 µm) was arranged serially in a stack with smallest mesh screen at the bottom and the largest at the top. Spice powder was loaded on the top sieve and the stack was shaken for 20 min [8]. The fractions retained on each screen were removed and weighed, and the weight fraction was calculated.

2.4 Estimation of RRSB Model Constants

For modeling particle size distribution of ground spice powders, a term ϕ, defined as the ratio of cumulative weight of comminuted particles retained on a sieve having size D (m) and net weight of comminuted particles was used as shown in Eq. (1),

$$\phi = \frac{Cumulative\ weight\ of\ comunited\ particles\ retained\ on\ sive}{Net\ weight\ of\ comunited\ particles} \quad (1)$$

Values of ϕ and sieve size D (m) can be related by Rosin-Rammler-Sperling-Bennet (*RRSB*) distribution equation as shown in Eq. (2) [9],

$$\phi = \exp\left[-\left(\frac{D}{M}\right)^n\right] \quad (2)$$

where, M and n are constants. Values of M and n can be estimated by fitting a straight line between $\log_e(D)$ and $\log_e(\log_e(1/\phi))$, which can be obtained from experimental data on sieve size D (m) and mass w (kg) of particles retained on each of the sieves. Slope of the line is equal to n. Values of M can be obtained by equating the intercept of the straight line to the parameter ($-n \times \log_e(M)$), where, M is the diameter above which 36.8% (i.e., ϕ= 0.368) of ground particles would lie. This M is termed as 'statistical average diameter' of ground particles. 'n' represents degree of uniformity of particles having size around the statistical average diameter, M. Higher the value of n, greater will be the uniformity of ground particles around the statistical average diameter [3].

2.5 Estimation of Rosin-RammlerModel Constants

For modeling the particle size distribution of finely ground particles, produced in milling, plot of log [log 100/(100-y)], or log [log 100/R], vs. log of D (sieve size) are plotted, where y is the cumulative percentage passing through D and R is the cumulative percentage retained on D. Such plots are known as Rosin-Rammler plots.

The Rosin-Rammler distribution is expressed as:

$$R = 100 \exp\left[-\left(\frac{D}{M}\right)^n\right] \quad (3)$$

where, R is cumulative mass percentage retained on sieve size D (m)

M is the size parameter (statistical average diameter), and
n is the distribution parameter (uniformity index)

Values of M and n can be estimated by fitting a straight line between log (log (100/R) and log (D), which can be obtained from experimental data on sieve size D (m) and mass w (kg) of particles retained on each of the sieves. Slope of the line will be equal to n. Values of M can be obtained by equating the intercept of the straight line to (-n × $\log_e$ (M)). M is the diameter above which 36.8% of ground particles would lie.

2.6 Mean Sizes of Ground Particles and Surface Area Created

Median diameter D_{med} (m) of the ground particles is the diameter, which will divide ground particles equally into two halves, i.e., 50% of particles would lie above and 50% below this diameter. Its value can be obtained by putting ϕ = 0.5 and $D = D_{med}$into Eq. (2).

Mode diameter D_{mod}(m) is the diameter at which $d\phi/dD$ is maximum. Value of $d\phi/dD$ is obtained through differentiation of Eq. (2) as shown in Eq. (4).

$$\frac{d\varphi}{dD} = \exp\left[-\left(\frac{D}{M}\right)^n\right] - \frac{nD^{n-1}}{M^n} \quad (4)$$

Mass mean diameter D_m(m) of ground particles is the sum of the product of particle diameter D and fraction $\Delta\phi$ of particles having diameter D. This can be expressed in differential form as shown in Eq. (5).

$$D_m = \int_0^1 D d\varphi \quad (5)$$

Value of D_m can be estimated from the area under the curve plotted between D and ϕ *from* Eq. (2).
Surface area of a sphere is six times the volume of a sphere divided by its diameter. If ground particles were composed of spherical bodies of diameter D_1, D_2, . . . ,D_n having the respective mass fractions of $\Delta\phi_1, \Delta\phi_2 ... \Delta\phi_n$, total surface area A_t ($m^2 kg^{-1}$) of the particulate solids will be $\sum_{j=1}^{n} \frac{6\left(\frac{\Delta\phi_j}{\rho}\right)}{D_j}$. This can be written in differential form as $\int_0^1 \frac{6}{\rho}\frac{d\phi}{D}$, where ρ (kg m^{-3}) is the density of the particles and (1/ρ) is the volume of particles having mass one kilogram.

Volume surface mean diameter or Sauter Mean Diameter, D_s (m) is defined as six times the ratio of volume of one kilogram of ground particle (which are assumed to be spherical) [3] and its surface area. Value of D_s can be estimated from the following equation:

$$D_s = \frac{6\left(\frac{1}{\rho}\right)}{\int_0^1 \frac{6d\phi}{\rho D}} = \left[\int_0^1 \frac{d\phi}{D}\right]^{-1} \quad (6)$$

Initial size of spice is its equivalent diameter D_i (m) which can be computed from its length, breadth and thickness [10] as shown in Eq. (7).

$$D_i = [\mathrm{L.B.T}]^{\frac{1}{3}} \quad (7)$$

where, L (m), B (m), and T (m) are the length, breadth and thickness of the spices respectively.

Sphericity (ψ) of a particle is defined as the ratio of surface area of a sphere having the same volume as that of the particle and actual surface area of the particle as shown in Eq. (8):

$$\Psi = \frac{\text{surface area of sphere having the same volume as that of particle}}{\text{Actual surface of the particle}}$$

For spice, initial sphericity[10], $\psi_i$can be computed from the Eq. (9).

$$\psi_i = \frac{[\mathbf{L.B.T}]^{\frac{1}{3}}}{\mathbf{L}} \quad (9)$$

Since, surface area of a sphere is six times the volume of the sphere divided by its diameter, initial surface area of spice seed A_i ($m^2\,kg^{-1}$) will be used as shown in Eq. (10).

$$A_i = \frac{6\left(\frac{1}{\rho}\right)}{\psi_i D_i} \quad (10)$$

where, ρ ($kg\,m^{-3}$) is the true density of spices.

2.7 Total New Surface Area Created in Grinding

The surface area of a fine particulate material is large and can be an important parameter. Most reactions are related to the surface area available. So, the surface area can have a considerable bearing on the properties of the material. In grinding operation fracture of material takes place and new surface is created. The total surface created is proportional to the power consumed. Finer the particle more is the total surface area generated. Total surface area A_t ($m^2\ kg^{-1}$) of ground particle created by both hammer and pin mills are given in Eq. (11)

$$A_t = \frac{1}{\psi_o}\int_0^1 \frac{6}{\rho}\frac{d\phi}{D} = \frac{6}{\psi_o \rho D_s} \quad (11)$$

where, $\psi_o$is the sphericity of ground particles and D_s (m) is the Sauter mean diameter or Volume surface mean diameter of ground particles. Value of the sphericity, $\psi_o$may be assumed as one for the present study [3].

2.8 Bond's Work Index

Generalized equation for the rate of change of energy requirement W ($kWh\ t^{-1}$) with change in size D (m) of particles is given as shown in Eq. (12) [4]

$$\frac{dW}{dD} = -\left(\frac{C}{D^N}\right) \quad (12)$$

where, C and N are constants.

Solution of Eq. (12) for initial size D_i and final size $D_o$is given by Eq. (13) as

$$W = \frac{C}{N}\left[\frac{1}{D_o^{N-1}} - \frac{1}{D_i^{N-1}}\right] \quad (13)$$

Value of N has been found to lie between 1 and 2. For brittle materials, N = 1 and for tough ones, N = 2. Bond's law considers that the value of N = 1.5 [3].

Bond's work index W_i($kWh\ t^{-1}$) for size reduction of a feed is defined as the energy ($kWh\ t^{-1}$) required for reducing the material from an infinite size (i.e. $D_i = \alpha$) to 80% (i.e., ϕ = 0.2) of ground materials passing through 100 micron sieve (i.e. $D_o = 100\times10^{-6}$ m).

Putting $W = W_i$, $N = 1.5$, $D_i = \alpha$ and $D_o = 100\times10^{-6}$ into Eq. (13) we get,

$$\frac{C}{N} = W_i\sqrt{100\times10^{-6}} \quad (14)$$

Putting N = 1.5 and the expression for C/N from Eq. (14) into Eq. (13) following expression for Bond's work index, W_i ($kWh\ t^{-1}$) is obtained as shown in Eq. (15),

$$W = \frac{W_i}{100}\left[\frac{1}{\sqrt{D_o}} - \frac{1}{\sqrt{D_i}}\right] \quad (15)$$

where, D_o (m) is the sieve size through which 80% of ground particles would pass. D_i (m) is taken as the sieve size through which 80% (i.e., ϕ = 0.2) of the feed would pass. W ($kWh\ t^{-1}$) is the energy required for grinding the feed.

In order to calculate parameters of *RRSB* model along with model constants, mean sizes of particles, Bond's work index, initial and total surface area created in grinding MATLAB version 7.10.0.499 (R2010a) was used for programming.

2.9 Specific Energy Consumption

The energy consumed in grinding per unit mass is important because too much finer grinding may not be advisable as it may not allow easy movement of the intake in the human intestine and too big particle size of the ground seed may not be desirable as it may reduce the bioavailability of the constituents [11]. Specific energy is the amount of energy required to grind per unit mass of the ground seed. It can be expressed in $kJ\ kg^{-1}$. The power requirement, size of the ground particle and increase in the total surface area are the functions of initial size, material nature, strength of the particle, shape, hardness, smoothness, brittleness, stickiness and moisture content in the material to be ground; type of mechanical device used for grinding and the mechanical parameters fixed for the grinding. Significance of power consumption in grinding lies in (a) economy of the grinding system and (b) quality of the finished product [12]. The specific energy consumed (S_E) expressed as ($kJ\ kg^{-1}$) can be expressed as shown in Eq. (16)

$$S_E = \left(\frac{P_C}{F_R}\right) \quad (16)$$

where, P_C is the total amount of power consumed in grinding a given mass of spice and is expressed in (kJ), F_R is the feed rate of spice and is expressed in ($kg\ h^{-1}$).

2.10 Flow Characteristics of Spice Powders

For characterization of flow behavior of the ground spice powders, its properties were determined.

2.10.1 Bulk Density of Porous Powder

Bulk density (ρ_p) of the porous powder was determined with the help of a measuring cylinder of 50 ml capacity. The upper layer of the powder within the measuring cylinder was leveled with the help of an iron strip. The height of the powder in the pipe was carefully observed and noted. The weight of the porous powder was also recorded [13, 14]. The volume and bulk density of the porous powder were determined using Eqs. (17) and (18),

$$V_p = \pi\left(R^2\right)H_p \quad (17)$$

and,

$$\rho_p = \frac{\text{mass of the porous powder}}{\text{volume of porous powder}}\left(\text{ kg m}^{-3}\right) \quad (18)$$

where, R is the inside radius of the measuring cylinder in (m), $H_p$is the height of the porous powder in the measuring cylinder in (m), and $V_p$is the volume of the porous powder contained in the measuring cylinder in (m^3).

2.10.2 Bulk Density of Compacted Powder

Spice powder in the measuring cylinder was tapped manually and vigorously with the help of a glass rod until it was fully compact [15]. The height of the tapped powder in the pipe was recorded and volume of the powder was calculated using Eq. (17). The compacted mass of the powder in the cylinder was also recorded. Thus, bulk density (ρ_c) of the compacted powder was determined using Eq. (18).

2.10.3 Hausner Ratio

Hausner ratio is a ratio of bulk density of compacted powder to that of porous powder of spices. This ratio gives an idea about the flowability of the powder. Hausner ratio can be obtained from Eq. (19),

$$H_r = \frac{\rho_c}{\rho_p} \quad (19)$$

where, H_r, represents the Hausner number; $\rho_p$and ρ_c are same as mentioned above.

Hausner ratio depends on frictional forces of spice powder, whereas angle of repose is mainly dependent on cohesive forces [11]. Hausner ratio gives indication about flowability of powder in loosely packed state.

2.10.4 Carr Index (CI)

Carr index (*CI*) is a ratio. It gives an idea about flowability of the powder. It can be determined with the help of Hausner index values as given in Eq. (20),

$$CI = 100 - \left(\frac{100}{H_r}\right) \quad (20)$$

2.10.5 Compressibility Index (CPI)

CPI is a ratio that gives idea about the extent to which a particular powder can be compressed. Spice powder was filled in a measuring cylinder whose height and inner diameter were known. Volume of spice powder in the pipe was calculated using Eq. (17). Powder in the pipe was subsequently tapped manually with the help of a glass rod at the rate of 1.79 taps s^{-1} under 1.88×10^5 (kg m^{-2}) force [15, 16]. Height and inner diameter of the compacted owder were noted and by using Eq. (17) volume of the compacted powder was calculated. The *CPI* was measured by the following expressions (Eqs. 21-23):

$$V_p = \pi\left(R\right)^2 H_p \quad (21)$$

$$V_c = \pi\left(R\right)^2 H_c \quad (22)$$

$$CPI = \frac{\left[\frac{V_p - V_c}{V_p}\right]}{100} \quad (23)$$

where, $V_p$is the porous powder volume (kg m^{-3}) and V_c is the volume of powder after tapping (kg m^{-3}).

3. RESULTS AND DISCUSSION

After grinding the spices in pin and hammer mills, sieve analysis was performed. The weight fraction was noted and used to plot the particle size distribution of cinnamon, coriander and turmeric powders ground in pin and hammer mills. Fig. 3 shows the particle size distribution curves of the spices.

Estimation of *RRSB* and *Rosin-Rammler* model parameters, mean sizes of ground particles, initial surface area of particles, total surface area created, and bond's work index are reported in the following sections.

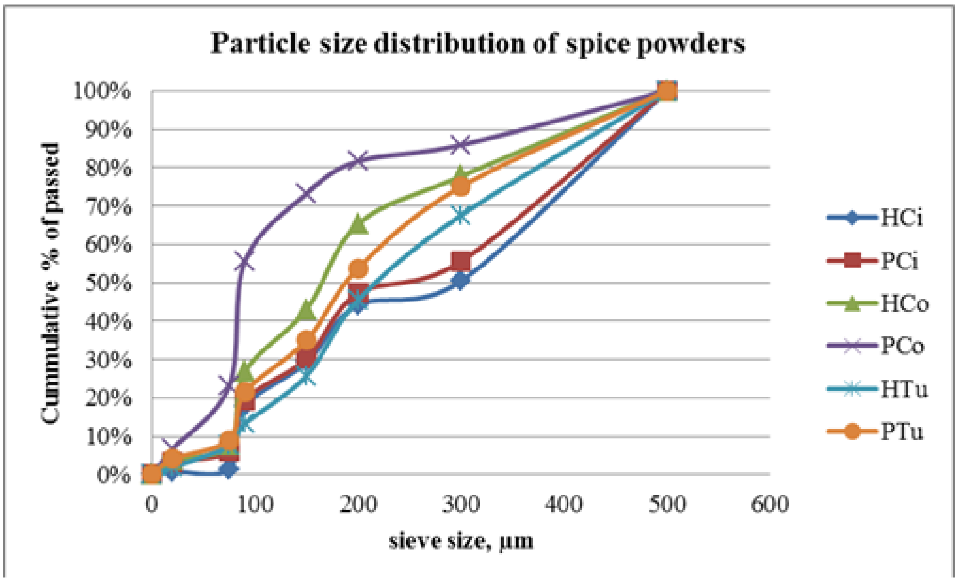

Fig – 1: Particle size distribution of cinnamon, coriander and turmeric spice powders ground in pin and hammer mill

3.1 Estimation of RRSB and Rosin-Rammler Model Parameters

Particle size distribution of ground spice powders were modeled using *RRSB* Eq. (2). The degree of uniformity '*n*' and statistical average diameter '*M*' for the spice powders ground in pin and hammer mills were calculated. In a study on modeling of particle size distribution due to the effect of high pressure, pressurization time and heat treatment temperature on reconstituted cow milk, the degree of uniformity values ranged from 0.931 – 1.318 [17]. In the present study, the degree of uniformity values ranged from 1.034 – 1.222, for the three selected spices ground in pin and hammer mills as shown in Table1 from which it is observed that the statistical average diameter for cinnamon and coriander are comparatively less when ground in hammer mill than that in pin mill. Similarly the degree of uniformity is higher for cinnamon and coriander powders ground in hammer mill than that in pin mill. In the case of turmeric powder, the statistical average diameter is less in pin mill when compared to that for hammer mill. Even though the degree of uniformity is higher for hammer mill indicating that the ground powder obtained from hammer mill has greater statistical average diameter than that ground in pin mill.
]
The average diameter (*M*) in the powders ground in hammer mill obtained with the help of Rosin-Rammler model are in agreement with the observations as mentioned above. The model predicted that cinnamon and coriander got lesser statisticalaverage diameter (*M*), even though the uniformity index (*n*) is slightly lesser for coriander in hammer compared to that of pin mill. In the case of turmeric the statistical average diameter (*M*) was less for the powder ground in pin mill and the uniformity index (*n*) was high when compared to the powder ground in hammer mill.

Table 1 – Parameters of *RRSB* and *RR* models

Sample code	*RRSB*		*RR*	
	n	*M* (mm)	*n*	*M* (mm)
PC_i	1.03	0.126	2.4	0.439
HC_i	1.04	0.107	1.7	0.413
PC_o	1.07	0.311	1.9	0.322
HC_o	1.09	0.174	1.6	0.233
PT_u	1.07	0.173	1.9	0.362
HT_u	1.22	0.256	1.8	0.411

where, *n* – of both *RRSB* and *RR* models indicating the uniformity of ground particles around statistical average diameter; *M* – of both *RRSB* and *RR* models indicating statistical average diameter of ground particles;

Following graphs show the experimental and predicted value of both *RR* and *RRSB* models. Residuals of *RR* and *RRSB* models are shown in the appendix Table A1 and A2 respectively.

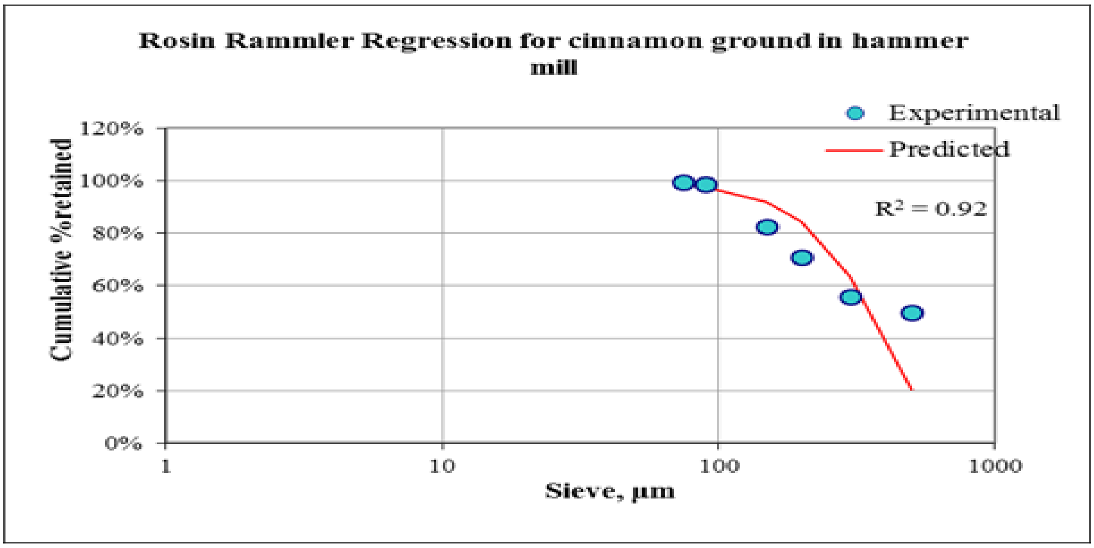

Fig. – 2(a): shows the graphical representation of Rosin Rammler regression for cinnamon ground in hammer mill

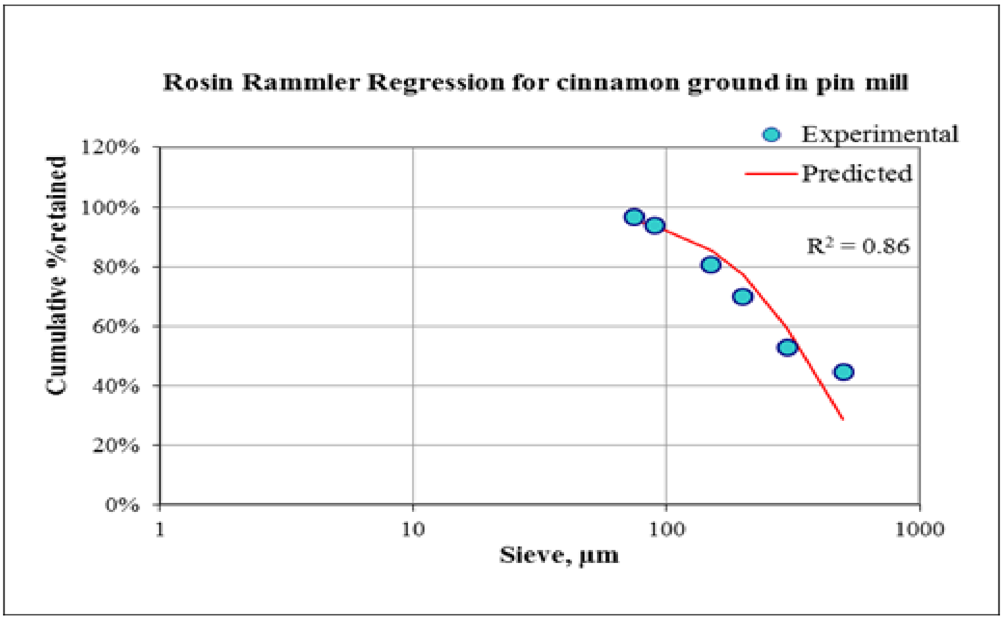

Fig. – 2(b): shows the graphical representation of Rosin Rammler regression for cinnamon ground in pin mill

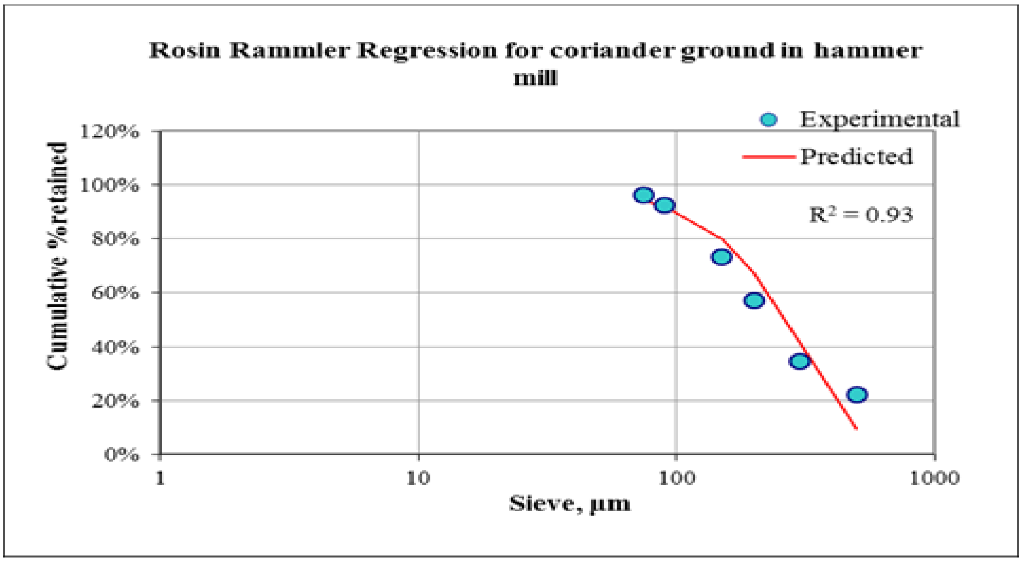

Fig. – 3.(a): shows the graphical representation of Rosin Rammler regression for coriander ground in hammer mill

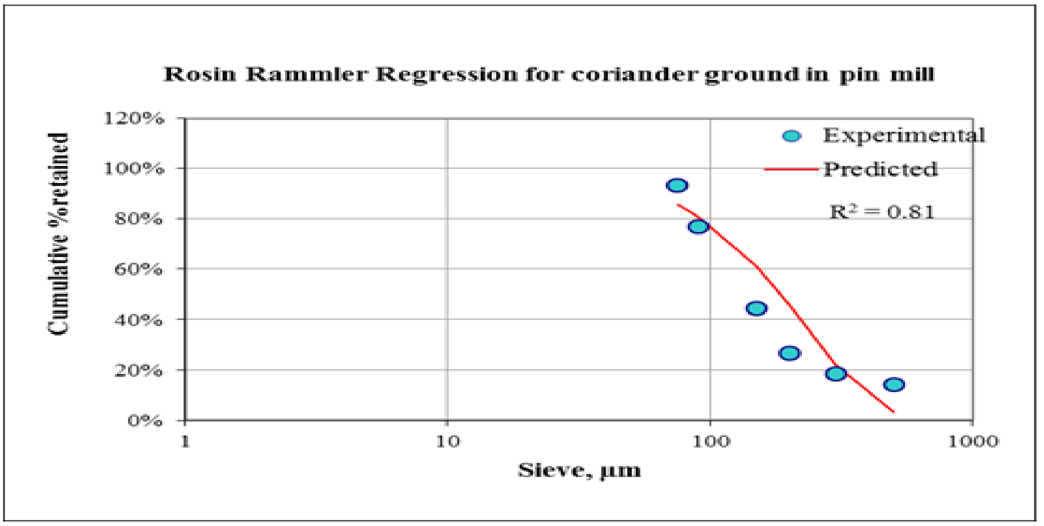

Fig. – 3.(b): shows the graphical representation of Rosin Rammler regression for coriander ground in pin mill

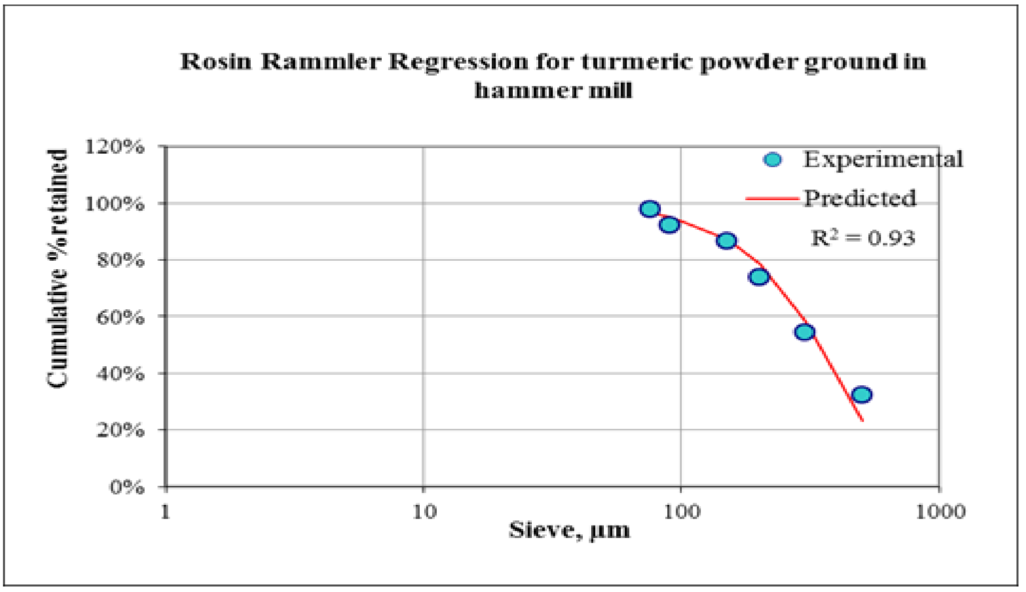

Fig. – 4.(a): shows the graphical representation of Rosin Rammler regression for turmeric ground in hammer mill

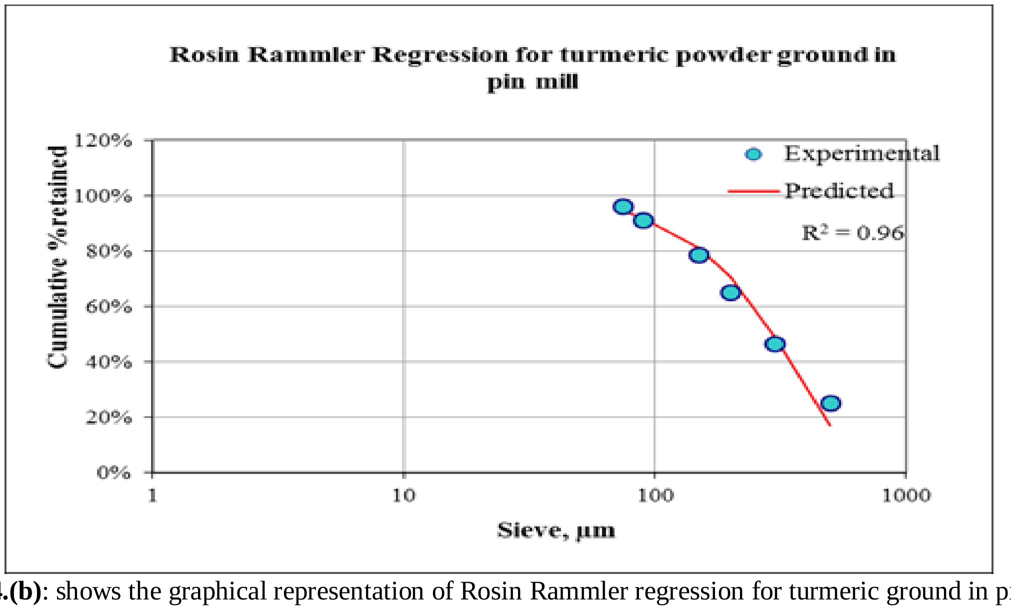

Fig. – 4.(b): shows the graphical representation of Rosin Rammler regression for turmeric ground in pin mill

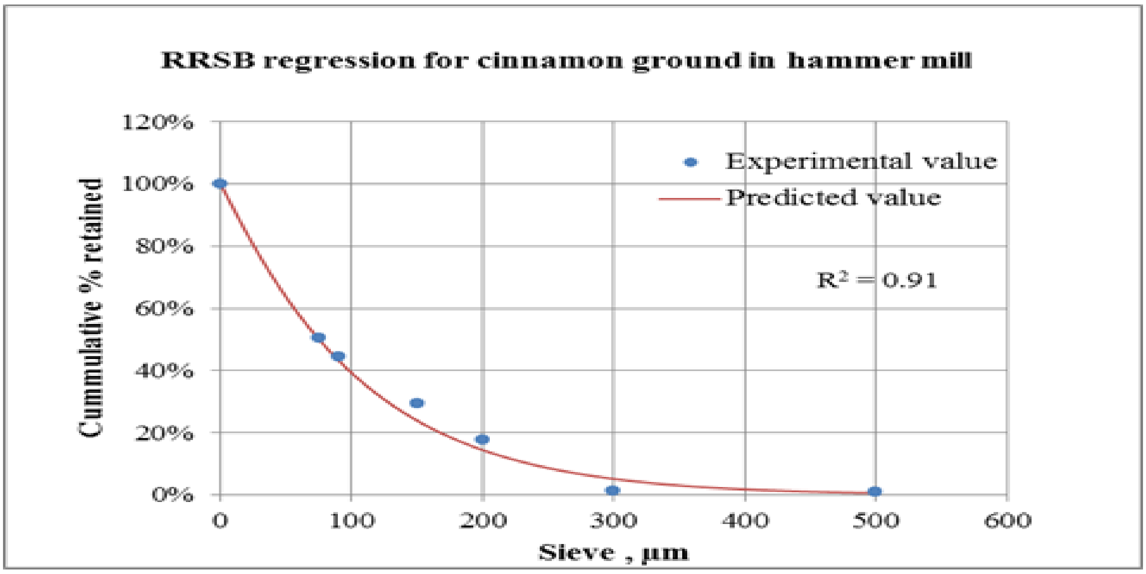

Fig. – 5.(a):shows the graphical representation of *RRSB* regression for cinnamon ground in hammer mill

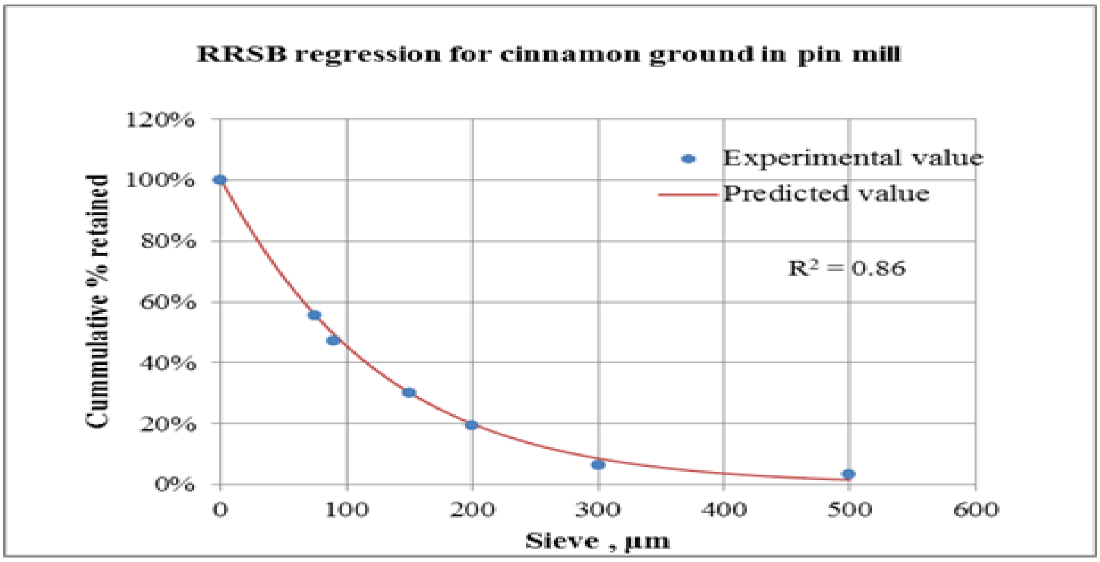

Fig. – 5.(b):shows the graphical representation of *RRSB* regression for cinnamon ground in pin mill

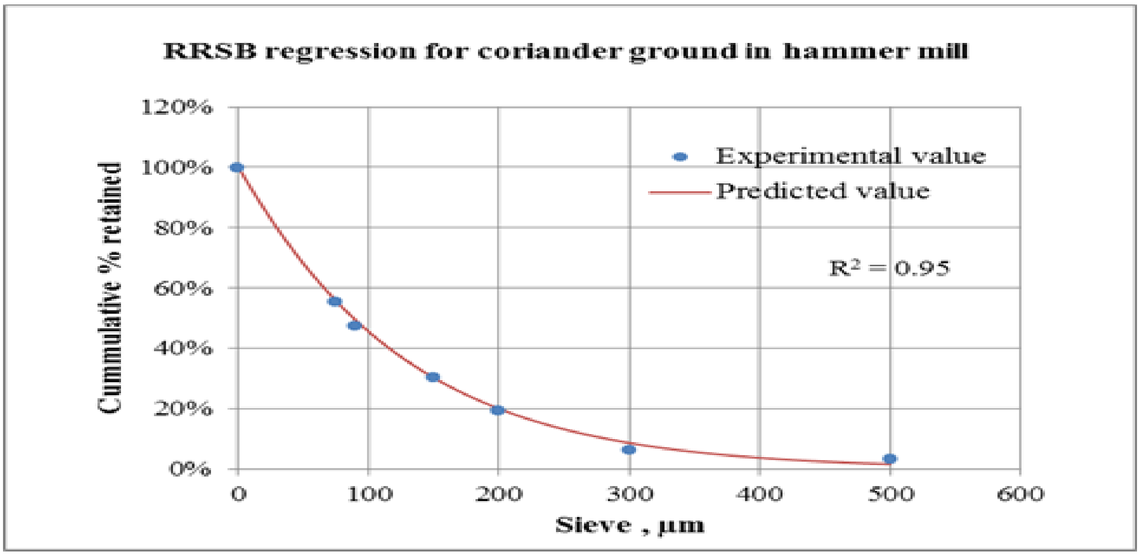

Fig. – 6.(a):shows the graphical representation of *RRSB* regression for coriander ground in hammer mill

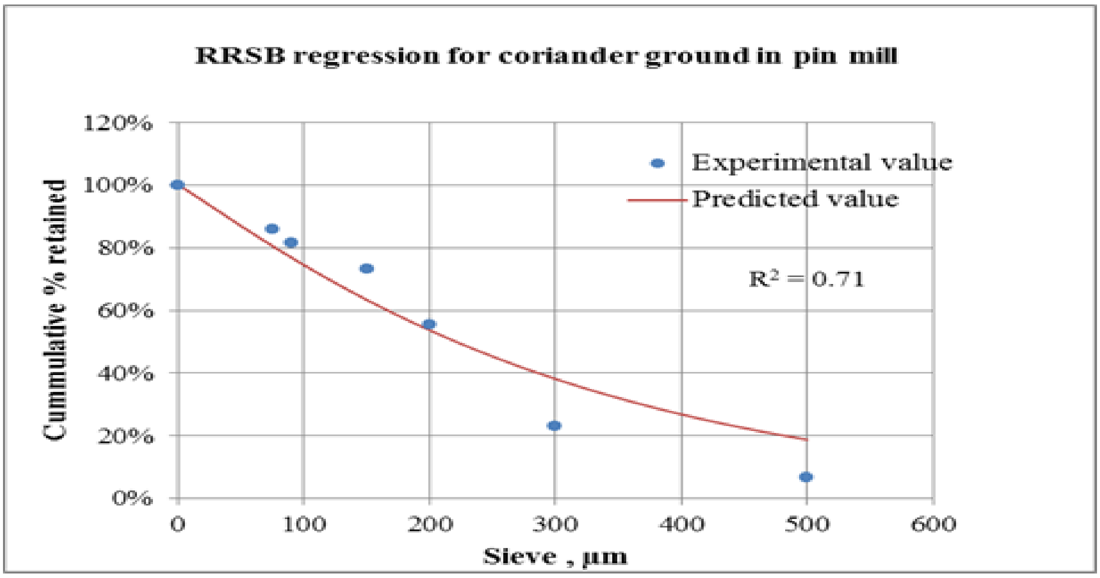

Fig. – 6.(b):shows the graphical representation of *RRSB* regression for coriander ground in pin mill

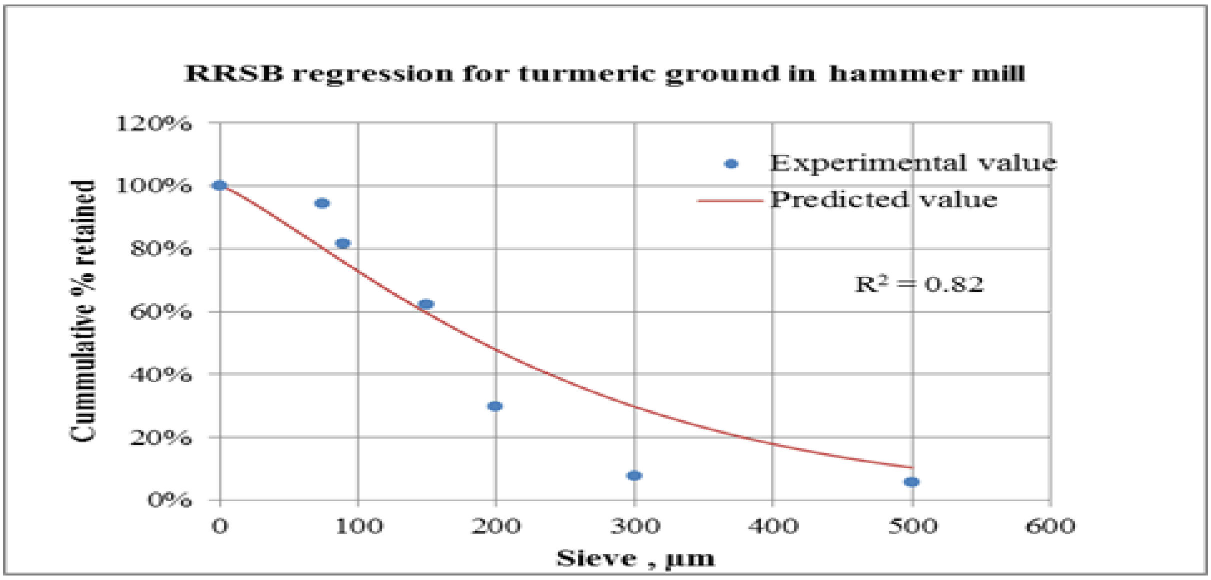

Fig. – 7.(a):shows the graphical representation of *RRSB* regression for turmeric ground in hammer mill

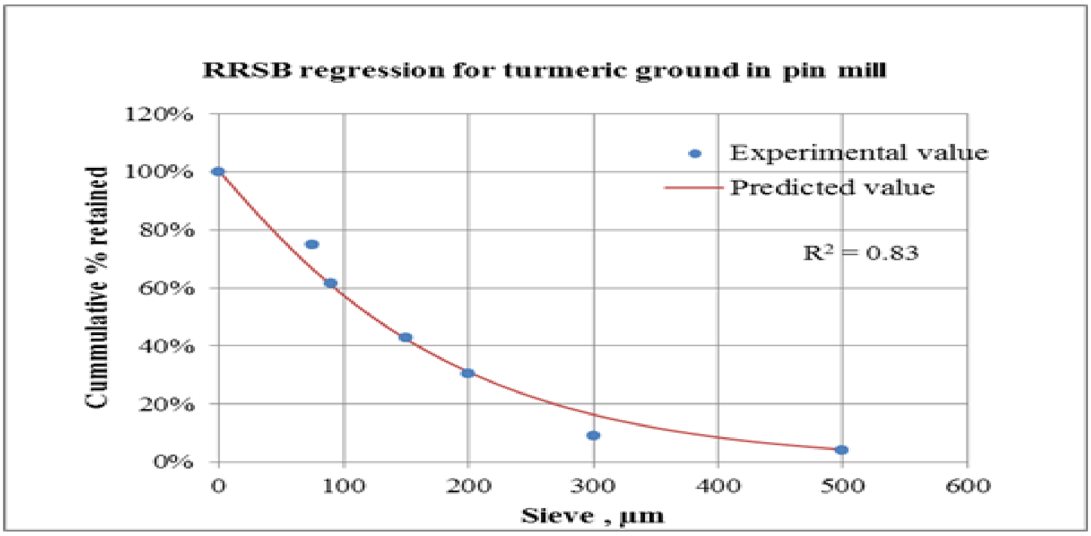

Fig. – 7.(b):shows the graphical representation of *RRSB* regression for turmeric ground in pin mill

3.2 Mean Sizes of Ground Particles and Total New Surface Area Created

Mean size of particles like Median diameter D_{med}, Mode diameter D_{mod}, Mass mean diameter D_m, Volume surface mean diameter or Sauter Mean Diameter D_s, are also listed in Table 1. In the case of cinnamon and coriander it is observed that mean size particles are less for hammer mill than that for pin mill. This indicates that the ground cinnamon and coriander powders in hammer mill have finer particle size compared to that ground in pin mill. It is also clear from Table 1 that higher total surface area of ground powders for cinnamon and coriander were obtained from hammer mill compared to that in pin mill. The main reason for increase in total surface area of ground powders obtained from hammer mill than that from pin mill was due to the fact that finer particles were obtained from hammer mill than that from pin mill.

3.3 Bond's Work Index

Table – 2: Mean sizes of particles, initial and total surface area created in grinding, Bond's work index

Sample code	D_{med} (mm)	D_{mod} (mm)	D_m (mm)	D_s (mm)	A_i (m^2kg^{-1})	A_t (m^2kg^{-1})	D_o (mm)	W_i ($kWh\ t^{-1}$)
PC_i	0.089	0.005	0.115	0.014	29.8	23444.0	0.200	3378.4
HC_i	0.075	0.006	0.101	0.012	29.8	26107.0	0.168	2786.9
PC_o	0.221	0.028	0.157	0.038	2.5	200.2	0.483	7143.0
HC_o	0.125	0.018	0.141	0.023	2.5	335.2	0.270	4597.5
PT_u	0.123	0.014	0.140	0.021	1.1	210.7	0.269	1998.2
HT_u	0.190	0.063	0.170	0.050	1.1	89.3	0.378	2690.9

where D_{med} – median diameter; D_{mod}– mode diameter; D_m – mass mean diameter; D_s – volume-surface area mean diameter or Sauter mean diameter; A_i – initial surface area of spices; A_t – total surface area of ground spice; D_o – sieve size through which 80% of the ground particles would pass; W_i – Bond's work index.

From the Table 2 it is clear that Bond's work index (W_i) was less for cinnamon and coriander powders ground in hammer mill compared to that from pin mill. In the case of turmeric, W_i was less for pin mill compared to that for hammer mill. W_i depends upon the fineness of the product. Literature reports indicate that $W_{i,}$ ranges from a low value of 80 to a value as high as 42220 kWh t^{-1} depending on the type of material used, viz., for Carrot (80 – 1610 kWh t^{-1}) [18], for Gum karaya (497 – 757 kWh t^{-1}) [19], for Pepper (4610 – 42220 kWh t^{-1}) [20], for Wheat (1580 – 2050 kWh t^{-1}), for Maize (81 – 283 kWh t^{-1}) [21] and for Coconut residue (206 kWh t^{-1}) [22]. Surprisingly, low values of $W_{i,}$ ranging between 40 and 80 kWh t^{-1} have been reported for grinding cumin seed in an attrition mill depending on feed rate and temperature of the grinder [23].

3.4 Energy consumption

Table – 3: Energy, Power and Specific energy consumption of Pin and Hammer mills during grinding of spices

	E_g (kWh)	F_r (kgh^{-1})	G_t (h)	s_w (g)	N_{ec} (kWh)	N_{ecm} (kWh $100g^{-1}$)	P_c (kW)	S_E (kJ kg^{-1})
P_E	0.823	-	0.167	-	-	-	-	-
H_E	0.800	-	0.167	-	-	-	-	-
PC_i	1.229	9	0.167	200	0.406	0.203	1.215	486.09
HC_i	1.170	9	0.167	200	0.371	0.185	1.110	443.82
PC_o	1.435	9	0.167	300	0.612	0.204	1.221	488.44
HC_o	1.405	9	0.167	300	0.606	0.202	1.209	483.74
PT_u	1.188	9	0.167	350	0.365	0.104	0.624	249.59
HT_u	1.029	9	0.167	200	0.229	0.115	0.687	274.75

where, P_E – Pin mill operated without any feed; H_E – Hammer mill operated without any feed; Eg – gross energy consumed during grinding; F_r – feed rate for grinder; G_t – grinding time; s_w – sample weight; N_{ec} – Net energy consumed during sample grinding; N_{ecm} – Net energy consumed in grinding per unit mass of sample; P_c – power consumed in grinding unit mass of sample; S_E – specific energy consumed.

In the present study, specific energy consumed per unit mass for grinding in hammer mill in the case of cinnamon and coriander were found to be 443.82 and 483.74 kJ kg^{-1} respectively as shown in Table 3. Whereas, in case of pin mill, the specific energy consumed per unit mass for grinding the same spices were found to be 486.09 and 488.44 kJ kg^{-1} respectively. This indicates that for both the spices, namely, cinnamon and coriander, the specific energy consumed was more in case of pin mill compared to that for hammer mill. Similar trend was also noted in the case of net energy consumption for the same two spices ground in the same two mills as stated earlier. To the contrary, specific energy consumed per unit mass in the case of turmeric ground in pin mill, was lesser (249.59 kJ kg^{-1}), compared to that for hammer mill (274.75 kJ kg^{-1}). Similar trend was noted in the case net energy consumed in grinding per unit mass which was less for pin mill (249.59 kJ kg^{-1}) than that for hammer mill (274.75 kJ kg^{-1}). Literature reports of specific energy consumption in the case of spices indicate that for fenugreek, specific energy consumption was 212.4 – 720 kJ kg^{-1}[12], and that for cumin was 99.4 – 132.8 kJ kg^{-1} using rotor mill [23].

3.5 Flow Characteristics of Spice Powders

Table – 4(a): Flow characteristics of spice powders ground in Pin and Hammer mills.

Sample code	*w*(g)	*h* (cm)	h_c (cm)	r_c (cm)	*v* (g cm^{-3})	v_c (g cm^{-3})	ρ_p (kg m^{-3})	ρ_c (kg m^{-3})
PC_i	10	9.033	5.367	1.075	32.789	19.480	305	513
HC_i	10	8.033	5.317	1.075	29.160	19.299	343	518
PC_o	10	13.29	7.410	1.075	48.252	26.897	207	372
HC_o	10	9.327	6.103	1.075	33.854	22.154	266	406
PT_u	10	6.023	4.690	1.075	21.864	17.024	457	587
HT_u	10	7.207	4.900	1.075	26.159	17.786	382	562

where, *w* – weight of spice powder taken for measurement; *h* – height of spice powder in volumetric cylinder; h_c – height of compacted spice powder in volumetric cylinder; r_c – inner radius of measuring cylinder; v_c – volume of compact powder; *v* – volume of porous powder; ρ_c– bulk density of compact powder; ρ_p – bulk density of porous powder

Table – 4(b): Flow characteristics of spice powders ground in Pin and Hammer mills.

Sample code	Hausner ratio	Carr index	*CPI* (ratio)
PC_i	1.682	40.546	40.590
HC_i	1.510	33.784	33.817
PC_o	1.797	44.355	44.258
HC_o	1.526	34.483	34.560
PT_u	1.284	22.147	22.136
HT_u	1.471	32.028	32.007

where*CPI* – compressibility index .

Particle size affects the flow characteristics of powder [11]. In general, bulk density can be increased by reducing particle size to increase the weight of a feed ingredient or complete feed per unit volume. Coriander and Cinnamon powder obtained from hammer mill had finer particle size compared to pin mill, so powders obtained from hammer mill had higher bulk density values compared to that for powders obtained from pin mill. From Table 4(a) & (b) results indicate that bulk density of the samples varied from 207 – 457 kg m^{-3}, bulk density of compacted powder varied from 372 – 587 kg m^{-3}, carr index varied from 22.147 – 44.355 , *CPI* varied from 22.136 – 44.258. The Hausner ratio and Carr's index are both measures of the flow properties of powders. A Hausner ratio of <1.25 indicates a powder that is free flowing whereas >1.25 indicates poor flow ability. The smaller the Carr's Index the better the flow properties. Carr's index is a measure of powder bridge strength and stability, and the Hausner ratio is a measure of the interparticulate friction [24][25]. From Table 4 it is observed that the hausner ratio, carr index and cpi ratio were lesser for cinnamon, coriander ground in hammer mill than in pin mill and for turmeric ground in pin mill than in hammer mill. Hausner Ratio and carr index were found to increase with increase in mean particle diameter indicating difficulties in flow [26].

Lesser values of sauter mean diameter of particle, bonds work index, specific energy consumption, power required for grinding and higher surface area created after grinding indicates better grinding performance for cinnamon, coriander in hammer mill and pin mill for turmeric. The probable reason might be the higher fiber content and smaller sizes of spices. Brittle material can be impacted and sheared well, compared to the fibrous material in pin mills. Thus cinnamon and coriander had better grinding performance in hammer mill while turmeric had better grinding performance in pin mill.

4. CONCLUSION

The following conclusions were observed from the present study on Modeling of size reduction, particle size analysis and flow characteristics of spice powders ground in hammer and pin mills:

- *RRSB* and *RR* models were useful in determining degree of uniformity and statistical average diameter for the ground products. Uniformity index and statistical average diameter obtained through hammer milling were preferable for cinnamon and coriander; whereas the case of in pin mill for turmeric.

- Mean sizes of ground particles, Bond's work index, specific energy consumption for grinding, and flow characteristic of coriander and cinnamon spices were lesser in hammer and in pin mill for turmeric. This indicates that finer powder was obtained in hammer mill for cinnamon and coriander; whereas, in the case of pin mill for turmeric.
- This present study was helpful in deciding suitability of mills for grinding of turmeric, cinnamon and coriander spices.

Grinders are designed on the basis of physical properties of biomaterials, at the same time physical properties vary very widely from one commodity to other in the case of food and pharmaceuticals. Availability of literature on this kind of study is very scarce, so the present study will help in identifying the right kind of grinder which is more suitable for grinding a particular commodity.

ACKNOWLEDGEMENTS

The authors acknowledge the support rendered by the NAIP, ICAR for the project on cryogenic grinding and also thank to the Research Centers (IISR, Kozhikode, India; NRCSS, Ajmer, Rajasthan, India; IISR, Calicut, India) for the supply of turmeric, coriander seed and cinnamon spices required for this study.

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