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Research Article

Grinding Characteristics of Coriander Seed with Reference to Physical Properties and Energy Consumption

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Abstract: Coriander (*Coriandrum sativum*) at three moisture contents (5.7, 11.4 and 17.2%, db) were ground using a micro pulverizer hammer mill with different grinder screen openings (0.5, 1.0 and 1.5 mm) and feed rates (8, 16 and 24 kg/h) at 3000 rpm. Specific energy consumption was found to decrease from 204.67 to 23.09 kJ/kg for increased levels of feed rate and grinder screen openings. The highest specific energy consumption was recorded for 17.2 % moisture content and 8 kg/h feed rate with 0.5 mm screen opening. Average particle size decreased from 0.99 to 0.47 mm with the increase of moisture content and decrease in grinder screen opening. It has been observed that the average particle size was minimum at 0.5 mm screen opening and 8 kg/h feed rate. Bond's work index and Kick's constant were increased from 0.61 to 3.07 kWh/kg, and 0.073 to 0.324 kWh/kg with the increase of moisture content, feed rate and grinder screen opening, respectively. Size reduction ratio and grinding effectiveness of coriander seed were found to decrease from 4.92 to 2.29 and 0.002 to 1.600 with the increase of moisture content, feed rate and grinder screen opening. The loose and compact bulk densities varied from 210 to 475 kg/m^3 and 231 to 550 kg/m^3, respectively for various mass fractions of sieve analysis. Bond's work index and Kicks constants were affected significantly by feed rate and moisture content for all screen openings except 0.5 mm.

***Keywords*:** grinding, coriander, sieve analysis, particle size

1. Introduction

Coriander (*Coriandrum sativum*) is an annual herb in the family of *Apiaceae* and native to southern Europe and North Africa to southwestern Asia. It has been used as a folk medicine for the relief of anxiety and insomnia in Iran. Experiments in mice support its use as an anxiolytic. India is the largest producer of coriander which is used extensively in curry powder [1]. The seeds of coriander are almost ovate globular with longitudinal ridges on the surface. The length of seed is 3-5 mm and color, when dried, is usually brown, but may be green, straw-colored or off white. The most important constituents of coriander seeds are essential oil and fatty oil. The essential oil and fat content of dried coriander seeds vary from 0.03% to 2.6, and 9.9% to 27.7%, respectively. Other constituents viz., crude protein, crude fiber and ash contents vary from 11.5% to 21.3%, 28.4% to 29.1% and 4.9 to 6.0, respectively [2, 3]. In holistic and

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traditional medicine, coriander is used as a carminative and digestive aid.

The size reduction is primarily used for conservation of energy, increasing surface area, pore size of the material and number of contact points in the compaction process [4, 5] and densification process [6]. Hammer mills are relatively cheap, easy to operate and suits for wide range of particles. Energy consumption of grinding biomass depends on initial particle size, moisture content, material properties, feed rate of the material and machine variables [7]. Recently, several investigators [8-12] have used the hammer and attrition mill for size reduction and particle size analysis of different agricultural materials. The specific energy requirement of hammer mill for grinding coastal Bermuda grass with different moisture content and feed rate [13]. The cryogenic grinding of cumin seed and cloves at different conditions and reported its influence on volatile oil content and components, particle size distribution, volume mean diameter and specific energy consumption [14, 15]. Various grinding characteristics of raw and parboiled rice are evaluated [16]. The influence of varietal difference, temperature and particle size on thermal properties of cryoground coriander, grinding characteristics of dried and roasted dehulled soybean splits, moisture content on engineering properties of kodo and kutki millets and grinding parameters of fenugreek seed [17-20]. This present work analysed grinding characteristic of coriander seed with reference to physical properties and energy consumption.

2. Materials and methods

2.1 *Materials preparation*

Coriander seed was procured from local market (Punjab, India) and cleaned manually by removing adhered foreign matter, immature and split ones, if any. The initial moisture content of the coriander was determined [21]. Initially the seeds were stored at room temperature (25°C), care was taken to attain the even moisture distribution. The initial moisture content was 7.0% db. [22]. For experimentation, predetermined quantity using equation (1) [23] of coriander was dried at 50°C air temperature in a recirculatory tray dryer (M/s BTPL, India) to achieve desired moisture content level (5.7%, db). To achieve high moisture content (11.4 and 17.2% db), calculated amount of water using equation (2) was added and mixed. Samples were packed in low-density polyethylene pouches and kept at 5°C for 24 h for uniform distribution of moisture throughout. Before experimentation, pouches were allowed to attain the room temperature [24].

$$X = \text{Dry Matter} \times \left[\frac{(\text{Initial moisture content, \% db} - \text{Required moisture, \% db})}{100} \right] \tag{1}$$

$$\text{Weight required after drying process} = (\text{Total weight of the material}) - X$$

$$W_2 = \frac{W_1(100 + M_1)}{(100 + M_o)} \tag{2}$$

where, X = amount of water to be added/removed, ml; Mo = initial moisture content, % db; M_1 = final moisture content, % db;

W_1 = initial weight of sample, g, and W_2 = final weight of the sample, g.

2.2 *Grinding and differential sieve analysis*

A micro pulverizer-hammer mill (swing type, Figure 1) (M/s. Osaw Agro Industries, India) fitted with a three-phase motor (3 HP, 3000 rpm) was used for grinding purpose. For each experiment, about 225 g sample in triplicate was ground using three different grinder screen openings (0.5, 1.0 and 1.5 mm) and feed rates (8, 16 and 24 kg/h). The grinding loss (%), moisture content and bulk density (loose and compact) of the ground material was determined [25]. For sieve analysis (Figure 2), a portion of ground sample was placed on the top of set of sieves (British Standards (BSS) sieve numbers viz., 14, 18, 30, 36, 52, 60, 85 and 100 and Pan) and shaken until reaches equilibrium, by inspecting and weighing at 5 min intervals after an initial sieving time of 10 min. The mass fractions collected on each sieve were weighed using a digital balance (TB-403, Denver Instruments, Bohemia, NY, having a least count of 0.001 g) and packed separately in zip lock polythene bags for further analysis.

Figure 1. Micro pulverizer-hammer mill (swing type)

Figure 2. Sieve Shaker, Vernier caliper

2.3 *Calculation of various parameters*

Bulk density (loose and compact) was determined thrice for mass fraction. From the volume of one grain, its diameter and hence the surface area was calculated [26]. All the calculated parameters are summarized below:

$$\text{Specific energy consumption} = \frac{(W_w - W_o) \times 3.6}{m} \tag{3}$$

Where, W_w and W_o are the power consumed by hammer mill at load and no-load conditions, Watts; m is the feed rate, kg/h.

$$\text{Size reduction ratio} = \frac{\text{Average size of feed}}{\text{Average size of product}} \tag{4}$$

$$\text{Grinding effectiveness} = \frac{\text{Surface area after grinding}}{\text{Surface area before grinding}} \tag{5}$$

$$\text{Weight of one particle} = (4/3)\pi(D_2/2)^3\rho \tag{6}$$

$$\text{Number of particles (N)} = \frac{\text{weight of one grain}}{\text{weight of one particles}} \tag{7}$$

$$\text{Surface area after grinding} = 4\pi(D_2/2)^2 N \tag{8}$$

Based on the mass fractions, average final particle size (D_2) was calculated using the following relationship;

$$\text{Average particle size } (D_2) = \sum_{i=1}^{n} \Phi_i d_i \tag{9}$$

The grinding energy per unit mass (E, kWh/kg) was calculated by the wattage of hammer mill, grinding time and feed rate. Based on the particle size (initial and final) and energy required to grind a unit weight of material, Bond's work index (W_i) and Kick's constant (K_K) was calculated [23].

$$E = K_K \ln\left(D_1/D_2\right) \tag{10}$$

$$E = 0.3162\ W_i\left(\frac{1}{\sqrt{D_2}} - \frac{1}{\sqrt{D_1}}\right) \tag{11}$$

where, D_1 and D_2 are the diameter of product and feed at 80% passes from sieve; ρ is the bulk density of particle.

2.4 *Statistical analysis*

The analysis of variance (ANOVA) test was carried out using AGRES statistical software, version 7.01 (Pascal International Software solutions, USA) and statistical procedures described by [20, 27] to examine the effect of moisture level and feed rate on grinding characteristics.

3. Results and discussion

3.1 *Physical characteristics of coriander seed*

The initial moisture content of coriander seed was recorded as 5.82% db. The seeds were conditioned to 5.7, 11.4 and 17.2% moisture content (db). The dimensions (major, medium and minor), geometric mean diameter, sphericity, surface area, thousand grain weight and bulk density were found to be varied in the range of 4.10-4.04 mm, 3.20-3.57 mm and 2.92-3.22 mm, 3.36-3.58 mm, 82.2-88.9%, 31.63-37.36 mm^2, 8.63-10.01g and 291-289 kg/m^3, respectively (Table 1).

Table 1. Various physical characteristics of coriander seed before grinding

Moisture content (%, db)	Dimensions (mm)			Geometric mean diameter (mm)	Sphericity (%)	Surface area (mm^2)	Thousand grain weight (g)	Bulk density (kg/m^3)
	Major	Medium	Minor					
5.7	4.10 ± 0.02	3.20 ± 0.02	2.92 ± 0.01	3.37 ± 0.01	82.2 ± 0.18	35.66 ± 0.20	8.63 ± 0.04	291 ± 17
11.4	4.10 ± 0.03	3.38 ± 0.01	3.07 ± 0.01	3.49 ± 0.01	85.1 ± 0.51	38.29 ± 0.11	9.71 ± 0.03	290 ± 13
17.2	4.04 ± 0.01	3.57 ± 0.02	3.22 ± 0.01	3.58 ± 0.03	88.5 ± 0.65	40.14 ± 0.74	10.01 ± 0.07	289 ± 11

3.2 *Grinding studies*

In Table 2, the maximum grinding loss at lower moisture content might be due to the formation of more fine powdered material that gets easily lost in the form of dust particles during the grinding process. During the grinding process, it was found that the temperature of grinder and product varied from 80-85°C and 70-75°C. Similar results were reported by [8].

Table 2. Grinding losses of coriander seed

Moisture content (%, db)	Feed rate (kg/h)	Grinding losses (g)		
		Screen opening (mm)		
		0.5	1.0	1.5
5.7	8	15.75^{e}	13.55^{g}	10.00^{d}
	16	15.00^{d}	13.22^{g}	9.31^{c}
	24	14.77^{c}	12.25^{f}	9.68^{c}
11.4	8	12.11^{b}	11.42^{e}	10.11^{d}
	16	12.08^{b}	11.31^{d}	10.10^{d}
	24	10.75^{a}	9.22^{c}	8.46^{b}
17.2	8	14.60^{c}	9.40^{c}	8.35^{b}
	16	14.44^{c}	9.00^{b}	8.00^{b}
	24	14.34^{c}	7.54^{a}	7.18^{a}

Means in columns with different superscripts are significantly different at $p \leq 0.05$

The specific energy consumption at load conditions on various moisture content and feed rates with grinder screen opening are depicted in Table 3.

Table 3. Specific energy consumption for grinding of coriander seed using hammer mill

Moisture content (%, db)	Feedrate (kg/h)	Specific energy consumption (kJ/kg) Screen opening (mm) 0.5	1.0	1.5
5.7	8	139.22^{f}	124.22^{d}	96.43^{d}
11.4		142.25^{g}	133.54^{e}	97.69^{d}
17.2		204.67^{h}	170.76^{f}	104.39^{e}
5.7	16	97.14^{c}	107.61^{c}	53.74^{b}
11.4		109.87^{d}	125.16^{d}	69.01^{b}
17.2		117.49^{e}	113.51^{c}	72.78^{c}
5.7	24	73.03^{a}	23.09^{a}	23.75^{a}
11.4		77.31^{a}	66.33^{b}	58.62^{b}
17.2		82.82^{b}	75.12^{b}	67.49^{b}

Means in columns with different superscripts are significantly different at $p \leq 0.05$

The average specific energy consumptions were decreased from 204.67 to 23.09 kJ/kg with increase of feed rate from 8 kg/h to 24 kg/h and grinder screen opening from 0.5 to 1.5 mm, respectively. The maximum specific energy consumption was found for 17.2% moisture content and 8 kg/h feed rate with 0.5 mm screen opening (Table 3). There exists a significant difference ($p \leq 0.05$) among the specific energy consumption at each level of moisture content, feed rate and grinder screen openings. The grinder equipped with smaller screen opening, consumed more specific energy due to the requirement of high energy for fine grinding. Similar results have been reported for grinding studies of alfalfa chops [5] and corn stover, switch grass, wheat and barley straw grind [6]. It has been reported that the specific energy consumption for grinding of corn stover at 6.2% (w.b.) moisture content of using a hammer mill of different screen opening (0.8, 1.6 and 3.2 mm) were 79.2, 53.28 and 25.2 kJ/kg respectively.

3.3 *Percent mass fractions retained*

The percent mass fractions retained in different sieves of differential sieve analysis are presented in Table 4.

It is clear from the result that the increase moisture content of coriander increase the percentage of medium size particles produced during grinding. However, the feed rate had significantly positive effect i.e. more fine particle were produced. This was attributed due to higher friction of force produced among the feed particles due to sufficient filling of the grinding cavity with the feed during grinding process and the increased feed rate. The results were in compliance with the results reported by [28] for makhana at different moisture and grinding time and [29] for peanut hull.

3.4 *Gravimetric characteristics*

Tables 5-6 illustrate the variation of bulk density (loose and compact) as a function of feed moisture content, feed rate and different sieve fractions.

The loose and compact bulk density varied from 210 to 475 kg/m^3 and 231 to 550 kg/m^3, respectively. The compact bulk density showed the maximum values as compared to loose bulk density, within the same particle range. It has been found that the loose and compact bulk densities were maximum at lower feed moisture content, screen opening and medium feed rate. Similar type of observations for various buckwheat seed milling fractions [30].

Table 4. Mass fractions (%) retained on various sieves after differential sieve analysis of coriander ground in hammer mill

Screen opening (mm)	Moisture content (%, db)	Feed rate (kg/h)	Mass fraction retained (%)								
			BSS Sieve number								
			14	18	30	36	52	60	85	100	Pan
0.5	5.7	8	1.0^{g}	5.6^{g}	7.7^{h}	16.0^{f}	45.8^{a}	14.7^{a}	9.0^{a}	0.2^{c}	0
		16	7.0^{c}	15.5^{d}	41.7^{b}	24.5^{a}	11.4^{f}	0.0	0.0	0.0	0
		24	0.0	15.3^{f}	23.5^{c}	23.8^{b}	25.8^{c}	6.6^{b}	4.2^{b}	0.7^{a}	0
	11.4	8	1.5^{f}	7.6^{e}	22.6^{c}	31.4^{a}	27.2^{b}	6.3^{b}	3.5^{c}	0.0	0
		16	5.4^{d}	16.7^{d}	44.6^{b}	17.5^{c}	13.2^{e}	1.2^{f}	1.1^{e}	0.4^{b}	0
		24	4.2^{e}	26.2^{b}	23.2^{c}	16.7^{d}	22.6^{c}	4.6^{c}	2.5^{d}	0.0	0
	17.2	8	21.8^{a}	21.6^{c}	17.4^{d}	15.0^{d}	20.0^{d}	3.3^{d}	1.0^{e}	0.0	0
		16	13.2^{b}	24.3^{b}	45.0^{a}	13.9^{d}	3.6^{g}	0.0	0.0	0.0	0
		24	21.8^{a}	29.7^{a}	17.3^{d}	12.4^{e}	13.3^{e}	2.5^{e}	2.8^{c}	0.1^{c}	0
1.0	5.7	8	2.7^{h}	6.4^{g}	15.7^{h}	19.2^{g}	36.2^{b}	12.3^{a}	7.2^{a}	0.3^{d}	0
		16	3.0^{h}	5.2^{g}	19.8^{g}	27.1^{c}	38.2^{a}	5.5^{b}	1.2^{f}	0.0	0
		24	6.2^{f}	12.4^{f}	25.1^{e}	28.0^{a}	25.2^{c}	2.5^{d}	0.7^{g}	0.0	0
	11.4	8	12.9^{e}	19.7^{d}	28.9^{c}	16.4^{f}	15.0^{e}	1.9^{e}	4.9^{b}	0.4^{a}	0
		16	4.6^{g}	15.0^{e}	49.3^{a}	23.0^{b}	8.1^{g}	0.0	0.0	0.0	0
		24	12.4^{d}	26.2^{b}	25.1^{d}	17.3^{e}	15.5^{d}	1.8^{e}	1.7^{e}	0.0	0
	17.2	8	21.3^{b}	25.1^{c}	17.2^{g}	15.3^{f}	14.1^{e}	3.6^{c}	3.1^{d}	0.3^{c}	0
		16	12.3^{c}	26.7^{a}	41.4^{b}	16.1^{d}	3.2^{h}	0.3^{g}	0.0	0.0	0
		24	32.4^{a}	24.3^{b}	17.2^{f}	11.8^{h}	9.1^{f}	1.5^{f}	3.3^{c}	0.4^{b}	0
1.5	5.7	8	3.2^{g}	6.7^{f}	33.1^{g}	31.9^{a}	23.6^{b}	1.5^{c}	0.0	0.0	0
		16	4.1^{e}	13.2^{d}	49.7^{a}	23.1^{c}	9.5^{d}	0.5^{f}	0.0	0.0	0
		24	5.3^{f}	13.3^{e}	26.8^{f}	26.5^{b}	24.4^{a}	2.9^{b}	0.8^{b}	0.0	0
	11.4	8	8.1^{e}	30.9^{b}	35.4^{c}	14.7^{f}	9.5^{d}	1.2^{d}	0.3^{c}	0.0	0
		16	4.5^{f}	25.2^{c}	45.2^{b}	20.4^{d}	4.7^{e}	0.0	0.0	0.0	0
		24	9.6^{d}	27.2^{c}	30.2^{e}	15.6^{f}	13.3^{c}	3.2^{a}	0.8^{a}	0.1^{a}	0
	17.2	8	24.6^{a}	28.5^{b}	20.0^{h}	13.9^{g}	12.3^{c}	0.7^{e}	0.0	0.0	0
		16	13.0^{c}	37.1^{a}	32.1^{d}	14.9^{e}	2.9^{g}	0.0	0.0	0.0	0
		24	19.9^{b}	35.4^{b}	30.4^{e}	11.0^{c}	3.3^{f}	0.1^{g}	0.0	0.0	0

Means in columns with different superscripts are significantly different at $p \leq 0.05$

Table 5. Loose bulk density on various sieves after differential sieve analysis of coriander in hammer mill

Screen opening (mm)	Moisture content (%, db)	Feed rate (kg/h)	Loose bulk density (kg/m³)								
			BSS Sieve number								
			14	18	30	36	52	60	85	100	Pan
0.5	5.7	8	360^{e}	371^{c}	356.4^{d}	378^{b}	358^{b}	314^{b}	324^{a}	233.3^{c}	0
		16	300^{g}	316^{f}	320^{e}	356^{c}	358^{b}	0	0	0	0
		24	0	373^{c}	384^{b}	404^{a}	368^{a}	305^{d}	273^{d}	300^{b}	0
	11.4	8	440^{b}	418^{b}	366^{c}	336^{d}	320^{c}	311^{c}	283^{c}	0	0
		16	475^{a}	274^{g}	296^{g}	314^{e}	302^{d}	400^{a}	264^{e}	400^{a}	0
		24	269^{h}	408^{a}	424^{a}	372^{b}	318^{c}	288^{e}	289^{c}	300^{b}	0
	17.2	8	376^{d}	362^{d}	280^{h}	306^{f}	298^{e}	292^{e}	300^{b}	0	0
		16	352^{f}	326^{e}	312^{f}	336^{d}	315^{c}	0	0	0	0
		24	386^{c}	426^{a}	308^{f}	304^{f}	284^{f}	256^{f}	268^{e}	300^{b}	0
1.0	5.7	8	300^{b}	259^{d}	314^{a}	346^{a}	342^{a}	282^{c}	292^{c}	244^{d}	333^{a}
		16	285^{c}	433^{a}	302^{b}	316^{a}	352^{a}	294^{c}	400^{a}	0	0
		24	256^{d}	292^{c}	320^{a}	322^{a}	294^{c}	291^{c}	345^{a}	0	0
	11.4	8	246^{e}	292^{c}	318^{a}	316^{a}	272^{c}	236^{d}	272^{c}	313^{b}	0
		16	221^{e}	330^{a}	314^{a}	320^{a}	290^{c}	0	0	0	0
		24	258^{d}	370^{b}	342^{a}	320^{a}	268^{c}	233^{d}	263^{c}	0	0
	17.2	8	306^{b}	280^{c}	258^{d}	278^{c}	276^{c}	252^{d}	278^{c}	300^{b}	0
		16	282^{c}	310^{b}	250^{d}	278^{c}	284^{c}	333^{a}	0	0	0
		24	324^{a}	324^{a}	256^{d}	272^{c}	252^{d}	210^{d}	268^{c}	267^{c}	0
1.5	5.7	8	300^{b}	303^{b}	322^{a}	340^{a}	326^{a}	289^{b}	0	0	0
		16	260^{c}	292^{b}	324^{a}	320^{a}	334^{a}	233^{d}	0	0	0
		24	295^{b}	348^{a}	372^{a}	354^{a}	304^{b}	264^{c}	275^{b}	0	0
	11.4	8	226^{e}	292^{b}	328^{a}	298^{b}	260^{b}	238^{e}	300^{b}	0	0
		16	230^{e}	280^{b}	318^{a}	314^{a}	282^{b}	0	0	0	0
		24	268^{c}	346^{a}	308^{b}	306^{b}	246^{c}	245^{c}	219^{f}	375^{a}	0
	17.2	8	278^{b}	292^{b}	258^{c}	242^{c}	232^{c}	218^{f}	0	0	0
		16	276^{b}	290^{b}	270^{c}	262^{c}	289^{b}	0	0	0	0
		24	334^{a}	294^{b}	252^{c}	248^{c}	268^{c}	367^{a}	0	0	0

Means in columns with different superscripts are significantly different at $p \leq 0.05$

Table 6. Compact bulk density on various sieves after differential sieve analysis of coriander in hammer mill

Screen opening (mm)	Moisture content (%, db)	Feed rate (kg/h)	Compact bulk density (kg/m^3)								
			BSS Sieve number								
			14	18	30	36	52	60	85	100	Pan
0.5	5.7	8	460^{c}	421^{e}	410^{d}	446^{b}	430^{a}	398^{b}	386^{a}	467^{b}	0
		16	350^{f}	372^{g}	378^{e}	412^{c}	432^{a}	0	0	0	0
		24	0	442^{c}	434^{c}	462^{a}	428^{a}	392^{b}	371^{b}	425^{c}	0
	11.4	8	500^{b}	464^{a}	450^{b}	418^{c}	420^{b}	367^{c}	383^{b}	0	0
		16	550^{a}	340^{d}	356^{g}	392^{d}	354^{c}	533^{a}	304^{e}	500^{a}	0
		24	306^{g}	452^{b}	478^{a}	422^{b}	374^{b}	348^{c}	347^{c}	500^{a}	0
	17.2	8	426^{d}	430^{d}	350^{g}	374^{e}	372^{b}	368^{c}	386^{a}	0	0
		16	384^{e}	382^{f}	364^{f}	388^{d}	376^{b}	0	0	0	0
		24	432^{d}	464^{a}	350^{g}	354^{f}	346^{d}	320^{d}	324^{d}	380^{d}	0
1.0	5.7	8	433^{a}	305^{d}	352^{c}	400^{a}	422^{a}	348^{b}	340^{c}	289^{d}	533^{a}
		16	312^{e}	517^{a}	346^{d}	368^{c}	386^{b}	306^{e}	500^{a}	0	0
		24	424^{b}	342^{d}	356^{b}	370^{c}	372^{c}	342^{c}	391^{b}	0	0
	11.4	8	282^{g}	320^{d}	350^{c}	358^{c}	330^{e}	291^{g}	320^{e}	413^{b}	0
		16	231^{h}	352^{c}	358^{b}	374^{b}	332^{e}	0	0	0	0
		24	304^{f}	410^{b}	400^{a}	364^{c}	320^{f}	310^{d}	329^{d}	0	0
	17.2	8	358^{d}	334^{d}	294^{f}	328^{d}	316^{g}	311^{d}	332^{d}	420^{a}	0
		16	314^{e}	330^{d}	300^{e}	322^{e}	340^{d}	467^{a}	0	0	0
		24	366^{c}	360^{c}	294^{f}	316^{f}	300^{h}	300^{f}	316^{e}	367^{c}	0
1.5	5.7	8	325^{c}	342^{d}	362^{e}	400^{a}	392^{b}	378^{c}	0	0	0
		16	360^{b}	356^{c}	382^{c}	390^{b}	410^{a}	433^{b}	0	0	0
		24	355^{b}	366^{b}	394^{a}	392^{b}	364^{c}	329^{d}	375^{b}	0	0
	11.4	8	266^{f}	350^{c}	388^{b}	366^{c}	320^{f}	319^{e}	400^{a}	0	0
		16	239^{g}	334^{e}	382^{c}	364^{c}	336^{d}	0	0	0	0
		24	292^{e}	402^{a}	376^{d}	350^{d}	302^{g}	318^{e}	281^{c}	575^{a}	0
	17.2	8	322^{c}	330^{e}	308^{f}	292^{g}	300^{g}	318^{e}	0	0	0
		16	308^{d}	320^{f}	298^{h}	324^{e}	313^{f}	0	0	0	0
		24	382^{a}	348^{d}	314^{f}	314^{f}	330^{e}	500^{a}	0	0	0

Means in columns with different superscripts are significantly different at $p \leq 0.05$

3.5 *Effect of treatments on various grinding characteristics*

The size reduction ratio and grinding effectiveness of coriander seed decreased from 4.92 to 2.30 and 0.001 to 1.600 with the increased level of moisture content, feed rate and grinder screen opening (Tables 7-8).

Size reduction ratio was found to be maximum at 8 kg/h feed rate, 0.5 mm hammer mill screen opening and 5.7% moisture content. The grinding effectiveness also found to be maximum for lower moisture content, lower feed rate and grinder screen opening. Table 9 describes the effect of treatments on the various grinding characteristics such as Bond's work index, kicks constant.

It was observed that the Bond's wok index and Kick's constant which are the measure of energy uptake were increased with the feed moisture level with grinder screen opening. This might be attributed to comparatively less grinding time taken to grind the unit feed with the increase of feed rate. Similar types of observations were reported by [11] on grinding characteristics of different legumes and for microwave dried maize grains [26].

3.6 *Analysis of variance*

ANOVA was carried out to examine the effect of treatments on various grinding characteristics viz. Bond's work index, kick's constant (Table 10).

Table 7. Effect of moisture content and feed rate on size reduction ratio of coriander seed

Moisture content (%, db)	Feed rate (kg/h)	Size reduction ratio		
		Screen opening (mm)		
		0.5	1.0	1.5
5.7	8	4.92^{a}	4.46^{a}	3.43^{a}
	16	2.91^{f}	3.96^{b}	2.93^{c}
	24	3.88^{c}	3.32^{c}	3.28^{b}
11.7	8	4.13^{b}	3.14^{d}	2.67^{f}
	16	3.18^{e}	3.03^{e}	2.76^{e}
	24	3.30^{d}	2.82^{g}	2.82^{d}
17.2	8	2.95^{f}	2.90^{f}	2.47^{g}
	16	2.70^{h}	2.64^{h}	2.44^{g}
	24	2.79^{g}	2.50^{i}	2.30^{h}

Means in columns with different superscripts are significantly different at $p \leq 0.05$

Table 8. Grinding effectiveness retained on various sieves after differential sieve analysis of coriander in hammer mill

Screen opening (mm)	Moisture content (%, db)	Feed rate (kg/h)	Grinding effectiveness (dimensionless)								
			BSS Sieve number								
			14	18	30	36	52	60	85	100	Pan
0.5	5.7	8	0.297^{b}	0.069^{d}	0.078^{d}	0.036^{d}	0.014^{e}	0.042^{c}	0.067^{b}	1.600^{a}	0.000
		16	0.004^{g}	0.005^{g}	0.009^{g}	0.010^{f}	0.013^{e}	0.000	0.000	0.000	0.000
		24	0.184^{c}	0.184^{c}	0.180^{b}	0.179^{a}	0.052^{c}	0.035^{d}	0.011^{f}	0.000	0.000
	11.4	8	0.096^{d}	0.051^{e}	0.015^{f}	0.015^{e}	0.022^{h}	0.315^{a}	0.000	0.000	0.000
		16	0.003^{i}	0.006^{g}	0.010^{g}	0.011^{f}	0.016^{e}	0.013^{f}	0.031^{c}	0.022^{b}	0.000
		24	0.067^{e}	0.360^{b}	0.208^{a}	0.144^{b}	0.179^{a}	0.041^{c}	0.024^{e}	0.000	0.000
	17.2	8	0.010^{f}	0.012^{f}	0.028^{e}	0.031^{d}	0.026^{d}	0.138^{b}	0.421^{a}	0.000	0.000
		16	0.003^{g}	0.005^{g}	0.009^{g}	0.010^{f}	0.015^{e}	0.000	0.000	0.000	0.000
		24	0.382^{a}	0.443^{a}	0.168^{c}	0.116^{c}	0.115^{b}	0.025^{e}	0.029^{d}	0.002^{c}	0.000
1.0	5.7	8	0.109^{c}	0.077^{d}	0.042^{d}	0.031^{e}	0.017^{e}	0.054^{c}	0.089^{c}	1.248^{a}	0.000
		16	0.004^{g}	0.004^{g}	0.009^{g}	0.011^{f}	0.014^{f}	0.021^{d}	0.019^{e}	0.000	0.000
		24	0.100^{d}	0.170^{c}	0.225^{b}	0.241^{a}	0.200^{a}	0.022^{d}	0.007^{f}	0.000	0.000
	11.4	8	0.029^{e}	0.019^{e}	0.019^{f}	0.033^{d}	0.043^{d}	0.346^{a}	0.113^{b}	0.608^{c}	0.000
		16	0.006^{g}	0.005^{g}	0.009^{g}	0.011^{f}	0.017^{e}	0.000	0.000	0.000	0.000
		24	0.221^{b}	0.395^{a}	0.248^{a}	0.164^{b}	0.135^{b}	0.018^{e}	0.018^{e}	0.000	0.000
	17.2	8	0.012^{f}	0.013^{f}	0.033^{e}	0.035^{d}	0.043^{d}	0.149^{b}	0.154^{a}	0.660^{b}	0.000
		16	0.004^{g}	0.005^{g}	0.011^{g}	0.012^{f}	0.016^{e}	0.014^{g}	0.000	0.000	0.000
		24	0.603^{a}	0.385^{b}	0.178^{c}	0.118^{c}	0.083^{c}	0.016^{f}	0.036^{d}	0.007^{d}	0.000
1.5	5.7	8	0.096^{c}	0.051^{d}	0.015^{e}	0.015^{f}	0.022^{f}	0.315^{c}	0.000	0.000	0.000
		16	0.004^{g}	0.005^{f}	0.009^{g}	0.010^{g}	0.014^{g}	0.015^{f}	0.000	0.000	0.000
		24	0.086^{d}	0.184^{c}	0.243^{c}	0.231^{a}	0.196^{a}	0.026^{e}	0.008	0.000	0.000
	11.4	8	0.042^{e}	0.010^{e}	0.012^{f}	0.031^{e}	0.060^{c}	0.415^{b}	1.259^{a}	0.000	0.000
		16	0.00	0.006^{f}	0.009^{g}	0.012^{g}	0.017^{g}	0.000	0.000	0.000	0.000
		24	0.172^{b}	0.416^{b}	0.302^{b}	0.150^{b}	0.117^{b}	0.032^{d}	0.008^{b}	0.001^{a}	0.000
	17.2	8	0.010^{f}	0.010^{e}	0.024^{d}	0.038^{d}	0.045^{d}	0.631^{a}	0.000	0.000	0.000
		16	0.004^{g}	0.006^{f}	0.011^{f}	0.012^{g}	0.017^{g}	0.000	0.000	0.000	0.000
		24	0.416^{a}	0.628^{a}	0.353^{a}	0.122^{c}	0.033^{e}	0.002^{g}	0.000	0.000	0.000

Means in columns with different superscripts are significantly different at $p \leq 0.05$

Table 9. Effect of moisture content and feed rate on grinding characteristics of coriander seed

Moisture content (%, db)	Feed rate (kg/h)	Screen opening (mm)					
		0.5		1.0		1.5	
		Bond's work index (kWh/kg)	Kicks constant (kWh/kg)	Bond's work index (kWh/kg)	Kick's constant (kWh/kg)	Bond's work index (kWh/kg)	Kick's constant (kWh/kg)
5.7	8	0.59^{g}	0.075^{i}	0.60^{g}	0.073^{h}	0.61^{i}	0.074^{h}
	16	1.15^{d}	0.135^{e}	0.84^{f}	0.106^{f}	1.06^{g}	0.125^{f}
	24	1.31^{c}	0.178^{c}	1.41^{c}	0.186^{c}	1.88^{c}	0.229^{c}
11.7	8	0.72^{f}	0.085^{i}	0.85^{f}	0.096^{g}	0.84^{h}	0.094^{g}
	16	1.09^{e}	0.127^{f}	1.19^{d}	0.137^{e}	1.22^{e}	0.137^{e}
	24	1.65^{b}	0.207^{b}	2.32^{b}	0.269^{b}	2.68^{b}	0.298^{b}
17.2	8	0.91^{e}	0.099^{h}	1.02^{e}	0.108^{f}	1.13^{f}	0.118^{f}
	16	1.36^{c}	0.147^{d}	1.45^{c}	0.156^{d}	1.48^{d}	0.156^{d}
	24	2.44^{a}	0.271^{a}	2.62^{a}	0.290^{a}	3.07^{a}	0.324^{a}

Means in columns with different superscripts are significantly different at $p \leq 0.05$

Table 10. ANOVA to examine the effect of moisture content and feed rate on grinding characteristics of coriander seed

Screening opening (mm)		Sources	Degrees of Freedom (DF)	Mean Square (MS)	F_{cal}	P-value
0.5	Bonds work index	Feed rate	2	0.851	12.653*	0.019
		Moisture content	2	0.246	8.663*	0.125
		Feed rate × Moisture content	4	0.067		
	Kicks constant	Feed rate	2	0.013	26.536*	0.005
		Moisture content	2	0.002	8.074*	0.155
		Feed rate × Moisture content	4	0.001		
1.0 mm	Bonds work index	Feed rate	2	1.356	26.964*	0.005
		Moisture content	2	0.434	8.640*	0.035
		Feed rate × Moisture content	4	0.050		
	Kicks constant	Feed rate	2	0.020	48.348*	0.002
		Moisture content	2	0.003	7.817*	0.042
		Feed rate × Moisture content	4	0.000		
1.5 mm	Bonds work index	Feed rate	2	2.321	45.066*	0.002
		Moisture content	2	0.377	7.329*	0.046
		Feed rate × Moisture content	4	0.052		
	Kicks constant	Feed rate	2	0.029	84.370*	0.001
		Moisture content	2	0.002	7.018*	0.049
		Feed rate × Moisture content	4	0.000		

* Significant at 5%

It was found that there exist a significant difference among all the grinding characteristics. The Kick's constant varied significantly with feed rate except moisture content of all grinding screen opening.

4. Conclusion

Dimensions (major, medium and minor), thousand grain weight, geometric mean diameter, sphericity, surface area and bulk density of coriander seed varied between 4.1-4.04 mm, 3.20-3.57 mm and 2.92-3.22 mm, 8.63-10.01 g, 3.36-3.58 mm, 82.2-88.9%, 31.63-37.36 mm^2 and 291-289 kg/m^3, respectively. During swing type hammer mill grinding, the specific energy was maximum for lesser screen opening and found decreased from 204.67 to 23.09 kJ/kg with increase of feed rate and grinder screen opening. The average particle size decreased from 0.99 to 0.47 mm and Bond's work index and Kick's constant were increased from 0.59 to 3.07 kWh/kg; 0.073 to 0.324 kWh/kg, respectively with the increase of moisture content, feed rate and grinder screen opening, respectively. Size reduction ratio and grinding effectiveness of coriander seed decreased from 4.92 to 2.30 and 0.001 to 1.600 with the increase of moisture content, grinder screen opening. The loose and compact bulk densities varied from 210 to 475 kg/m^3 and 230.77 to 550 kg/m^3, respectively of the various mass fractions of sieve analysis. The energy uptake measures viz., Bond's work index and Kick's constant were affected significantly on feed rate and moisture content on all screen openings.

Conflict of interest

The authors declare no competing financial interest.

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