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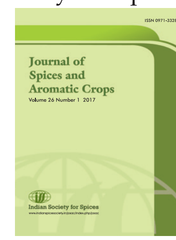

Determination of grinding parameters of fenugreek seed

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Abstract

Experiment to identify ambient grinding conditions and energy consumed was conducted for fenugreek. Fenugreek seeds at three moisture content (5.1%, 11.5% and 17.3%, d.b.) were ground using a micro pulverizer hammer mill with different grinding screen openings (0.5, 1.0 and 1.5 mm) and feed rate (8, 16 and 24 kg h^{-1}) at 3000 rpm. Physical properties of fenugreek seeds were also determined. Specific energy consumptions were found to decrease from 204.67 to 23.09 kJ kg^{-1} for increasing levels of feed rate and grinder screen openings. On the other hand specific energy consumption increased with increasing moisture content. The highest specific energy consumption was recorded for 17.3% moisture content and 8 kg h^{-1} feed rate with 0.5 mm screen opening. Average particle size decreased from 1.06 to 0.39 mm with increase of moisture content and grinder screen opening. It has been observed that the average particle size was minimum at 0.5 mm screen opening and 8 kg h^{-1} feed rate at lower moisture content. Bond's work index and Kick's constant were found to increase from 8.97 to 950.92 kWh kg^{-1} and 0.932 to 78.851 kWh kg^{-1} with the increase of moisture content, feed rate and grinder screen opening, respectively. Size reduction ratio and grinding effectiveness of fenugreek seed were found to decrease from 4.11 to 1.61 and 0.0118 to 0.0018 with the increase of moisture content, feed rate and grinder screen opening, respectively. The loose and compact bulk densities varied from 219.2 to 719.4 kg m^{-3} and 137.3 to 736.2 kg m^{-3}, respectively.

Keywords: fenugreek, grinding, particle size, sieve analysis

Introduction

Fenugreek or methi (*Trigonella foenum-graecum* L.) is a major spice of India and largest producer which is used extensively in curry powder (Blade 1998). It is native to south-eastern Europe and East Asia and now cultivated as a semi-arid crop and is widely favored in the states of India as a popular spice. Grinding is an important unit operation to increase the surface area and make it convenient to use in the culinary purposes. Various factors affect the power consumption in grinding operation e.g. structure of the material, grinding mechanism and operating parameters (Das 2005). Grinding

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is one of the most power consuming unit operations in which almost 99% of input energy is converted into heat due to friction whereas 1% is utilized for breaking the bond between particles. In conventional or ambient grinding of spices, temperature rises to the extent of 43-95°C (Singh & Goswami 1999) which causes the oil release and loss of aromatic and medicinal properties of spices. It makes ground product gummy, sticky and results in chocking of sieves (Singh & Goswami 1999). Temperature rise of the ground product is a major concern of the conventional grinding process and therefore it is necessary to perform the grinding under lower temperature conditions. 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 (Walde *et al.* 2002). Recently, several investigators (Goswami & Singh 2003; Solanki *et al.* 2005; Anthony & Tabil 2006; Indira & Bhattacharya 2006) have used the hammer and attrition mill for size reduction and particle size analysis of different agricultural materials. Mani *et al.* (2004) studied the grinding performance of Wheat and barley straws, corn stover and switchgrass at two moisture contents were ground using a hammer mill with three different screen sizes (3.2, 1.6 and 0.8 mm) and found switchgrass had the highest specific energy consumption (27.6 kW h t^{-1}) and corn stover had the least specific energy consumption (11.0 kW h t^{-1}) at 3.2 mm screen size. Von Bargen *et al.* (1981) reported that the corn residues required more grinding energy than wheat straw and grain sorghum residues in a hammer mill at constant peripheral speed (15.8 m s^{-1}). Singh & Goswami (1999b, 2000a) studied 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. Sharma *et al.* (2008) evaluated various grinding characteristics of raw and parboiled rice. Limited research information is available on grinding characteristics of spices. Therefore, the present work has been carried out to study the physical properties of fenugreek seed before and after grinding, grinding characteristics, colour attributes and sieve analysis of fenugreek to investigate the influence of ambient grinding conditions and energy consumed during grinding process.

Materials and methods

Fenugreek seed was procured from local market and cleaned manually by removing adhered foreign matter, immature and splitted ones, if any. The initial moisture content of the fenugreek was determined (AOAC 1995) and stored at room temperature (25°C) for 2 to 3 weeks. For experimentation, predetermined quantity using equation 1 (Sahay & Singh 2001) of fenugreek was dried at 50°C air temperature in a recirculatory tray dryer (M/s BTPL, India) to achieve desired moisture content level (5.1%, db). To achieve high moisture content (11.5% and 17.3% db), calculated amount of water using equation 2 (Murthy & Bhattacharya 1998) 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.

X = Dry matter × [(Initial moisture content, % d.b.) – (Required moisture, % d.b.) / 100] ..(1)

Weight required after drying process = Total weight of the material – X

$$W_2 = W_1 (100 + M_1) / (100 + M_o) \quad ..(2)$$

Where, Mo=initial moisture content; % db; M_1=final moisture content % d.b.; W_1=initial weight of sample, g, and W_2=final weight of the sample, g.

A micro pulverizer-hammer mill (swing type) (Osaw Agro Industies, India) fitted with a three-phase motor (3 HP, 3000 rpm) was used for grinding purpose. For each experiments, about 225 g sample in duplicate 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^{-1}). The grinding loss (%), moisture content and bulk density (loose and compact) of the ground material was determined. For sieve analysis, a portion of ground sample was placed on the top of set of sieves (1.201, 0.894, 0.500, 0.401, 0.295, 0.251, 0.177, 0.157 mm 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.

Bulk density (loose and compact) was determined thrice for mass fraction (Singh *et al.* 2008). From the volume of one grain, its diameter and hence the surface area was calculated (Velu *et al.* 2006). All the calculated parameters are summarized below:

Specific energy consumption =
$$[(W_w - W_o) \times 3.6] / m \quad ..(3)$$

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^{-1}. The Power consumption was measured using single element electro dynamic portable wattmeter (IMP Power Ltd. Mumbai).

Size reduction ratio = Average size of feed/ Average size of product ..(4)

Grinding effectiveness = Surface are after grinding / Surface area before grinding ..(5)

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

Number of particles (N) = Weight of one grain/ Weight of one particle ..(7)

$$\text{Surface are after grinding} = 4\,\pi\,(D_2 / 2)^2\,N \quad ..(8)$$

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

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

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 (Sahay & Singh 2001).

$$E = E_K \ln (D_1 / D_2) \quad ..(10)$$

$$E = 0.3162\, W_i\, [(1/\sqrt{D_2}) - (1/\sqrt{D_1})] \quad ..(11)$$

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.

The analysis of variance test (ANOVA) was carried out using Ag Res, version 7.01 (Pascal International Software solutions, USA) and statistical procedures described by Gomez & Gomez (1984) to examine the effect of moisture level and feed rate ($P<0.05$) on grinding characteristics.

Results and discussion

Physical characteristics of fenugreek seed

The initial moisture content of fenugreek seed was recorded as 5.82% d.b. The seeds were conditioned to 5.1%, 11.5% and 17.3% moisture content (d.b). 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 4.0- 4.17 mm, 2.4- 2.66 mm, 1.49-1.71 mm, 2.43-2.65 mm, 59.53-59.84%, 18.50-22.23 mm^2, 13.4-14.48 g and 851.25-794.74 kg m^{-3}, respectively (Table 1).

Grinding characteristics

Grinding loss was found to be maximum for lower moisture content and feed rate decreased with the increase of moisture content and feed rate (Table 2). The maximum loss at lower moisture content was due 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 75-85°C and 65-75°C, respectively. Similar results were reported by Singh & Goswami (2000b); Goswami & Singh (2003) for cumin seed. The specific energy consumption with various moisture content and feed rates with grinder screen opening is depicted in Table 3. The average specific energy consumptions decreased from 204.67 to 23.09 kJ kg^{-1} with increase of feed rate from 8 to 24 kg h^{-1} and grinder screen opening from 0.5 to 1.5 mm, respectively. The minimum specific energy consumption was found for 17.3% moisture content and 8 kg h^{-1} feed rate with 1.0 mm screen opening (Table 2). There exists a significant difference ($P<0.05$) 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 fine grinding requires high energy. Similar results have been reported for grinding studies of alfalfa chops (Ghorbani *et al.* 2010) and corn stover, switch grass, wheat and barley straw grind (Mani *et al.* 2004). It has been reported that the specific energy consumption for grinding of corn stover at 6.2% (w.b.) moisture content by 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^{-1} respectively.

Percent mass fractions retained

The percent mass fractions retained in different sieves of differential sieve analysis are presented in Table 3. It was found that the maximum materials retained were at 0.401 mm sieve size. The average particle size decreased from 1.60 to

Table 1. Physical characteristics of fenugreek seed

Moisture content (%, d.b.)	Dimensions (mm)			Geometric mean diameter (mm)	Sphericity (%)	Surface area (mm^2)	Thousand grain weight (g)	Bulk density (kg m^{-3})
	Major	Medium	Minor					
5.1	4.03	2.45	1.49	2.43	59.53	18.50	13.43	851.25
11.5	4.10	2.55	1.60	2.54	59.68	20.37	13.95	822.99
17.3	4.17	2.66	1.71	2.65	59.84	22.23	14.48	794.74

Table 2. Grinding losses, specific energy consumption, size reduction ratio of fenugreek seed

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Milling losses (g)			Specific energy consumption (kJ kg^{-1})			Size reduction ratio		
		Screen opening (mm)			Screen opening (mm)			Screen opening (mm)		
		0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5
5.1	8	17.46^{e}	17.08^{f}	16.41^{g}	139.22^{f}	124.22^{d}	96.43^{d}	3.73^{a}	3.54^{a}	4.11^{a}
	16	16.36^{d}	15.94^{e}	14.60^{e}	142.25^{g}	133.54^{e}	97.69^{d}	2.86^{c}	3.42^{c}	3.55^{c}
	24	13.92^{c}	13.39^{c}	12.54^{b}	204.67^{h}	170.76^{f}	104.39^{e}	3.22^{b}	3.48^{b}	3.72^{b}
11.5	8	16.30^{d}	15.05^{d}	15.02^{f}	97.14^{c}	107.61^{c}	53.74^{b}	2.87^{c}	2.64^{e}	2.19^{d}
	16	16.10^{d}	13.76^{b}	12.63^{d}	109.87^{d}	125.16^{d}	69.01^{b}	2.64^{d}	2.45^{g}	2.19^{d}
	24	14.94^{b}	13.77^{b}	10.26^{b}	117.49^{e}	113.51^{c}	72.78^{c}	2.25^{g}	2.54^{f}	1.77^{g}
17.3	8	15.07^{c}	13.74^{b}	13.38^{c}	73.03^{a}	23.09^{a}	23.75^{a}	2.53^{e}	2.16^{i}	2.06^{f}
	16	14.89^{b}	13.52^{b}	11.40^{c}	77.31^{a}	66.33^{b}	58.62^{b}	2.42^{f}	2.35^{h}	2.12^{e}
	24	10.92^{a}	12.18^{a}	9.31^{a}	82.82^{b}	75.12^{b}	67.49^{b}	2.07^{h}	2.80^{d}	1.61^{h}

Means in columns with different superscripts are significantly different at $P<0.05$

Table 3. Mass fractions (%) retained of various particle sizes of ground fenugreek

Screen opening (mm)	Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Mass fraction retained (%) Sieve size (mm) 1.201	0.894	0.500	0.401	0.295	0.251	0.177	0.157	Pan
0.5	5.1	8	6.90^{m}	25.11^{j}	37.24^{h}	81.43^{e}	74.71^{h}	62.32^{b}	54.49^{b}	5.51^{b}	0.00
		16	17.40^{l}	37.03^{h}	67.47^{b}	105.74^{b}	158.02^{a}	28.11^{g}	17.34^{i}	1.47^{e}	0.00
		24	15.36^{l}	29.90^{i}	41.15^{g}	93.89^{c}	123.28^{d}	56.23^{c}	34.67^{e}	0.80^{h}	0.00
	11.5	8	105.28^{j}	67.30^{f}	51.42^{e}	67.32^{g}	82.78^{g}	45.17^{e}	32.76^{e}	2.72^{d}	0.00
		16	117.33^{i}	78.10^{d}	52.49^{e}	73.24^{f}	102.68^{f}	27.49^{g}	28.38^{f}	1.49^{e}	0.00
		24	185.72^{g}	61.91^{g}	56.48^{d}	65.85^{g}	126.72^{d}	28.38^{g}	7.70^{l}	0.31^{l}	0.00
	17.3	8	169.61^{h}	65.95^{g}	49.78^{f}	68.42^{g}	107.82^{f}	43.46^{e}	11.21^{k}	0.17^{m}	0.00
		16	210.91^{f}	64.56^{g}	44.92^{g}	67.13^{g}	106.44^{f}	12.49^{k}	22.75^{h}	1.16^{f}	0.00
		24	280.34^{c}	82.50^{c}	51.79^{f}	54.86^{h}	65.81^{j}	37.67^{f}	7.64^{l}	0.51^{j}	0.00
1.0	5.1	8	3.83^{n}	13.84^{l}	29.86^{i}	77.37^{f}	141.01^{c}	50.45^{d}	46.11^{d}	1.71^{e}	0.00
		16	4.06^{n}	14.48^{l}	29.39^{i}	104.31^{b}	119.79^{e}	69.45^{a}	33.18^{e}	1.09^{f}	0.00
		24	9.43^{m}	19.25^{k}	46.00^{f}	94.27^{c}	107.05^{f}	43.31^{e}	47.15^{d}	3.42^{c}	0.00
	11.5	8	116.25^{i}	93.87^{b}	59.10^{c}	66.30^{g}	78.27^{g}	37.21^{f}	28.90^{f}	1.58^{e}	0.00
		16	120.86^{i}	85.53^{c}	60.49^{c}	88.15^{d}	101.90^{f}	31.46^{g}	15.87^{i}	0.68^{i}	0.00
		24	101.82^{j}	91.54^{b}	61.86^{c}	72.57^{f}	114.50^{e}	33.95^{f}	16.90^{i}	0.73^{i}	0.00
	17.3	8	230.61^{e}	86.70^{c}	56.87^{d}	57.79^{h}	109.77^{f}	18.04^{j}	7.22^{l}	0.49^{j}	0.00
		16	198.02^{g}	86.84^{c}	61.27^{c}	46.93^{i}	107.12^{f}	24.82^{h}	14.95^{j}	0.45^{k}	0.00
		24	53.39^{k}	73.20^{d}	138.24^{a}	128.55^{a}	20.62^{m}	38.75^{f}	30.16^{e}	0.68^{i}	0.00
1.5	5.1	8	4.17^{n}	8.02^{m}	16.55^{k}	67.27^{g}	116.00^{e}	30.36^{g}	66.27^{a}	7.96^{a}	0.00
		16	3.19^{n}	8.90^{m}	19.99^{k}	81.73^{e}	150.46^{b}	56.31^{c}	41.86^{c}	0.95^{g}	0.00
		24	4.13^{n}	8.03^{m}	23.62^{j}	80.39^{e}	123.99^{d}	57.00^{c}	48.74^{c}	2.51^{d}	0.00
	11.5	8	198.54^{g}	91.76^{b}	56.52^{d}	56.58^{h}	99.27^{f}	20.31^{i}	17.36^{i}	0.63^{j}	0.00
		16	195.28^{g}	108.48^{a}	62.84^{c}	59.98^{h}	71.27^{h}	20.30^{i}	21.27^{g}	1.57^{e}	0.00
		24	326.60^{b}	75.56^{d}	55.83^{d}	56.28^{h}	68.93^{i}	18.49^{j}	7.84^{l}	0.42^{k}	0.00
	17.3	8	293.56^{c}	71.78^{e}	42.19^{f}	44.76^{i}	105.13^{f}	11.07^{k}	13.09^{j}	0.40^{k}	0.00
		16	263.92^{d}	93.46^{b}	55.96^{d}	55.64^{h}	66.29^{k}	19.72^{j}	17.42^{i}	0.82^{h}	0.00
		24	431.00^{a}	74.62^{d}	46.61^{f}	38.79^{j}	58.58^{l}	3.05^{l}	7.86^{l}	0.22^{m}	0.00

Means in columns with different superscripts are significantly different at $P<0.05$

0.39 mm with increase of moisture content and grinder screen openings. It has been observed, the average particle size was minimum at 0.5 screen opening for 8 kg h^{-1} feed rate. It is clear from the result that the increase moisture content of fenugreek increase the percent 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 frictional force produced among the feed particles due to sufficient filling of the grinding

Table 4. Loose bulk density of various particle sizes of ground fenugreek

Screen opening (mm)	Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Loose bulk density (kg m^{-3}) Sieve size (mm) 1.201	0.894	0.500	0.401	0.295	0.251	0.177	0.157	Pan
0.5	5.1	8	533.4^{e}	637.4^{b}	625.8^{e}	701.0^{b}	638.4^{b}	449.6^{d}	482.6^{b}	390.8^{e}	351.6^{f}
		16	552.6^{c}	625.0^{c}	614.4^{f}	656.0^{f}	547.2^{h}	427.8^{e}	481.2^{b}	506.8^{a}	390.2^{d}
		24	543.6^{d}	604.8^{d}	657.0^{c}	665.6^{e}	584.2^{f}	485.0^{b}	458.8^{c}	385.0^{e}	343.2^{f}
	11.5	8	449.2^{j}	540.8^{g}	512.2^{k}	493.4^{l}	439.0^{m}	375.2^{g}	391.2^{f}	406.6^{d}	383.4^{d}
		16	394.6^{m}	505.8^{h}	530.8^{j}	510.0^{k}	457.2^{i}	425.6^{e}	425.0^{d}	389.6^{e}	355.4^{e}
		24	364.6^{o}	509.8^{h}	517.6^{k}	494.8^{l}	460.2^{i}	367.0^{h}	394.6^{f}	399.6^{d}	340.6^{g}
	17.3	8	402.0^{l}	427.2^{m}	441.4^{o}	459.0^{n}	401.4^{l}	379.2^{g}	385.6^{f}	421.2^{c}	220.0^{k}
		16	512.8^{g}	379.2^{n}	418.0^{p}	409.8^{p}	346.6^{m}	371.0^{g}	324.8^{h}	219.2^{i}	252.0^{i}
		24	444.0^{j}	450.2^{j}	481.0^{n}	404.6^{p}	421.2^{k}	376.4^{g}	432.6^{d}	398.2^{d}	328.0^{g}
1.0	5.1	8	377.4^{h}	592.2^{d}	681.4^{a}	672.2^{d}	531.2^{g}	420.2^{e}	418.0^{e}	378.4^{f}	238.0^{j}
		16	519.0^{f}	563.0^{f}	632.8^{e}	642.6^{g}	614.4^{d}	488.0^{b}	458.0^{c}	373.2^{f}	337.6^{g}
		24	390.0^{m}	623.6^{c}	668.4^{b}	658.2^{f}	625.2^{c}	432.6^{e}	406.2^{e}	337.8^{f}	279.2^{h}
	11.5	8	484.0^{h}	574.4^{e}	551.6^{i}	550.4^{i}	453.4^{i}	408.2^{f}	334.2^{h}	389.6^{e}	294.4^{h}
		16	458.8^{i}	512.6^{h}	571.6^{h}	525.4^{j}	499.8^{h}	421.8^{e}	392.6^{f}	431.0^{c}	345.8^{f}
		24	429.4^{k}	543.6^{g}	588.2^{g}	400.0^{o}	502.8^{h}	408.6^{f}	388.8^{f}	388.4^{e}	329.0^{g}
	17.3	8	393.8^{l}	436.0^{l}	445.6^{o}	475.0^{m}	414.0^{k}	356.8^{h}	344.2^{h}	245.0^{h}	355.6^{e}
		16	402.2^{l}	533.2^{g}	502.6^{l}	443.6^{n}	422.8^{j}	384.4^{g}	375.0^{g}	386.2^{e}	362.6^{e}
		24	443.6^{j}	490.0^{i}	449.2^{o}	466.8^{m}	438.0^{j}	378.8^{g}	363.8^{g}	373.0^{f}	320.0^{g}
1.5	5.1	8	454.6^{i}	442.8^{k}	641.4^{d}	657.0^{f}	598.6^{e}	556.8^{a}	487.2^{b}	408.4^{d}	394.6^{d}
		16	562.6^{b}	631.4^{a}	645.8^{d}	719.4^{a}	599.4^{e}	469.0^{c}	493.6^{a}	380.0e	220.0^{k}
		24	621.2^{a}	539.0^{g}	677.8^{b}	690.6^{c}	651.8^{a}	490.4^{b}	435.4^{d}	414.6^{d}	429.6^{c}
	11.5	8	431.4^{k}	529.2^{g}	571.4^{h}	582.8^{h}	491.6^{h}	452.2^{d}	408.4^{e}	289.0^{g}	356.0^{e}
		16	443.0^{j}	556.4^{f}	621.2^{e}	534.6^{j}	381.2^{l}	458.8^{c}	422.8^{d}	376.4^{f}	434.78^{b}
		24	457.4^{i}	556.8^{f}	656.2^{c}	530.6^{j}	509.2^{h}	396.4^{g}	428.8^{d}	428.6^{c}	427.6^{c}
	17.3	8	397.2^{l}	452.2^{j}	494.4^{m}	477.0^{m}	426.8^{j}	420.4^{e}	409.0^{e}	460.0^{b}	525.0^{a}
		16	401.4^{l}	504.0^{h}	502.8^{l}	516.6^{k}	513.8^{h}	380.2^{g}	405.4^{e}	356.0^{f}	188.2^{l}
		24	376.0^{n}	458.8^{j}	502.6^{l}	426.4^{o}	392.8^{l}	366.2^{h}	354.2^{g}	385.0^{e}	425.8^{c}

Means in columns with different superscripts are significantly different at $P<0.05$

cavity with the feed during grinding process with the increased feed rate. The results were in compliance with the results reported by Jha & Verma (1999) for makhana at different moisture and grinding time and Fasina (2008) for peanut hull.

Gravimetric characteristics

Tables 4-5 illustrates 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

Table 5. Compact bulk density of various particle sizes of ground fenugreek

Screen opening (mm)	Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Compact bulk density (kg m^{-3})								
			Sieve size (mm)								
			1.201	0.894	0.500	0.401	0.295	0.251	0.177	0.157	Pan
0.5	5.1	8	611.6^{b}	665.4^{a}	697.2^{d}	736.2^{b}	724.6^{a}	695.0^{a}	515.4^{d}	480.2^{d}	403.2^{e}
		16	577.2^{c}	642.2^{d}	659.0^{g}	691.6^{d}	671.2^{c}	527.8^{f}	559.4^{b}	574.2^{a}	405.8^{e}
		24	573.6^{c}	631.4^{e}	672.8^{f}	696.8^{d}	659.2^{d}	585.6^{d}	524.0^{c}	448.6^{f}	383.0^{f}
	11.5	8	497.8^{f}	589.4^{g}	560.8^{h}	556.8^{i}	491.8^{i}	438.8^{j}	470.6^{d}	461.2^{e}	453.8^{c}
		16	453.2^{g}	549.4^{i}	565.8^{h}	562.6^{i}	556.2^{g}	471.2^{i}	517.4^{d}	463.2^{e}	418.0^{d}
		24	417.4^{i}	521.6^{j}	540.0^{h}	533.6^{j}	511.2^{h}	441.2^{j}	462.6^{e}	445.2^{f}	411.6^{e}
	17.3	8	456.6^{g}	469.4^{k}	515.4^{i}	517.6^{k}	427.6^{j}	408.4^{k}	446.8^{e}	463.8^{e}	137.3^{j}
		16	540.2^{d}	423.4^{l}	453.6^{j}	478.0^{l}	429.2^{j}	399.8^{k}	430.4^{f}	238.8^{j}	366.6^{g}
		24	481.2^{f}	472.8^{k}	516.8^{i}	469.8^{l}	502.0^{h}	459.2^{i}	478.6^{d}	463.8^{e}	396.0^{f}
1.0	5.1	8	426.4^{h}	658.4^{c}	734.0^{a}	722.2^{b}	621.2^{e}	509.8^{g}	512.6^{d}	441.8^{f}	282.4^{h}
		16	540.2^{d}	661.6^{b}	681.4^{e}	739.2^{a}	680.2^{c}	560.8^{e}	516.8^{d}	447.0^{f}	417.8^{d}
		24	460.6^{g}	666.4^{a}	729.4^{b}	719.2^{c}	676.0^{c}	522.0^{g}	490.6^{d}	386.4^{h}	321.4^{g}
	11.5	8	515.0^{e}	602.4^{g}	603.8^{g}	593.0^{h}	522.4^{h}	443.2^{i}	418.2^{g}	420.0^{g}	345.2^{g}
		16	515.0^{e}	576.0^{h}	639.4^{g}	608.2^{g}	562.2^{g}	480.2^{h}	531.0^{c}	466.2^{e}	499.2^{b}
		24	488.6^{f}	593.0^{g}	619.6^{g}	622.8^{f}	601.4^{f}	519.8^{f}	481.0^{d}	519.0^{b}	430.0^{d}
	17.3	8	435.2^{h}	516.8^{j}	516.6^{i}	515.0^{k}	494.2^{i}	480.0^{h}	458.0^{e}	426.8^{g}	380.0^{f}
		16	459.4^{g}	573.0^{h}	530.6^{h}	517.4^{k}	530.6^{h}	480.8^{h}	472.8^{d}	448.6^{f}	534.5^{a}
		24	455.8^{g}	550.6^{i}	522.4^{h}	504.6^{k}	512.2^{h}	458.0^{i}	441.8^{e}	517.2^{b}	420.0^{d}
1.5	5.1	8	487.2^{f}	617.8^{f}	704.4^{c}	700.6^{c}	690.4^{b}	641.4^{b}	564.8^{b}	503.0^{c}	450.4^{c}
		16	602.0^{b}	663.8^{b}	646.0^{g}	737.8^{b}	635.4^{e}	568.0^{e}	603.4^{a}	480.2^{d}	260.0^{h}
		24	659.4^{a}	607.8^{g}	732.2^{a}	728.8^{b}	668.8^{c}	608.8^{c}	528.0^{c}	463.0^{e}	499.0^{b}
	11.5	8	449.6^{g}	580.4^{g}	681.0^{e}	634.8^{e}	567.2^{g}	530.2^{e}	485.8^{d}	397.4^{h}	396.0^{f}
		16	519.6^{e}	618.6^{f}	660.8^{f}	590.4^{h}	448.4^{j}	543.0^{e}	517.2^{c}	476.2^{e}	250.4^{h}
		24	457.8^{g}	596.8^{g}	691.2^{d}	598.2^{h}	584.0^{g}	482.4^{h}	477.8^{d}	475.0^{e}	496.2^{b}
	17.3	8	414.2^{i}	471.8^{k}	512.6^{i}	517.6^{k}	530.6^{h}	522.0^{f}	510.2^{c}	265.0^{i}	380.0^{f}
		16	418.0^{i}	516.0^{j}	530.4^{h}	538.6^{j}	571.4^{g}	491.0^{h}	530.0^{c}	460.2^{e}	240.2^{i}
		24	386.8^{j}	470.8^{k}	526.0^{h}	466.8^{l}	513.8^{h}	505.0^{g}	487.6^{d}	496.2^{d}	495.6^{b}

Means in columns with different superscripts are significantly different at $P<0.05$

density varied from 188.2 to 719.4 kg m^{-3} and 137.3 to 739.2 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 feed rate. Steadman *et al.* (2001) also reported the similar type of observations for various buckwheat seed milling fractions.

Table 6. Grinding effectiveness for fenugreek differential size reduction

Screen opening (mm)	Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Grinding effectiveness (dimensionless)								
			Sieve size (mm)								
			1.201	0.894	0.500	0.401	0.295	0.251	0.177	0.157	Pan
0.5	5.1	8	0.0049^{c}	0.0045^{b}	0.0043^{c}	0.0041^{b}	0.0041^{d}	0.0043^{d}	0.0058^{b}	0.0062^{c}	0.0074^{d}
		16	0.0042^{d}	0.0038^{d}	0.0037^{d}	0.0035^{c}	0.0036^{e}	0.0046^{d}	0.0043^{d}	0.0042^{e}	0.0060^{f}
		24	0.0046^{d}	0.0042^{c}	0.0039^{d}	0.0038^{c}	0.0040^{d}	0.0045^{d}	0.0050^{c}	0.0059^{d}	0.0069^{e}
	11.5	8	0.0036^{e}	0.0030^{d}	0.0032^{e}	0.0032^{d}	0.0037^{e}	0.0041^{d}	0.0038^{e}	0.0039^{f}	0.0040^{h}
		16	0.0037^{e}	0.0031^{d}	0.0030^{e}	0.0030^{d}	0.0030^{f}	0.0036^{e}	0.0032^{f}	0.0036^{g}	0.0040^{h}
		24	0.0035^{e}	0.0028^{e}	0.0027^{f}	0.0027^{e}	0.0029^{f}	0.0033^{f}	0.0032^{f}	0.0033^{h}	0.0035^{i}
	17.3	8	0.0032^{e}	0.0031^{d}	0.0028^{f}	0.0028^{e}	0.0034^{e}	0.0035^{e}	0.0032^{f}	0.0031^{i}	0.0105^{c}
		16	0.0025^{g}	0.0031^{d}	0.0029^{e}	0.0028^{e}	0.0031^{f}	0.0033^{f}	0.0031^{f}	0.0056^{d}	0.0036^{i}
		24	0.0024^{g}	0.0024^{f}	0.0022^{f}	0.0024^{f}	0.0023^{g}	0.0025^{h}	0.0024^{i}	0.0025^{j}	0.0029^{j}
1.0	5.1	8	0.0071^{a}	0.0046^{b}	0.0041^{c}	0.0042^{b}	0.0049^{a}	0.0059^{a}	0.0059^{a}	0.0068^{b}	0.0107^{b}
		16	0.0054^{c}	0.0044^{c}	0.0043^{c}	0.0039^{c}	0.0043^{c}	0.0052^{c}	0.0056^{c}	0.0065^{c}	0.0069^{e}
		24	0.0062^{b}	0.0043^{c}	0.0039^{d}	0.0040^{b}	0.0042^{c}	0.0055^{b}	0.0058^{b}	0.0074^{a}	0.0089^{c}
	11.5	8	0.0032^{e}	0.0027^{e}	0.0027^{f}	0.0028^{e}	0.0032^{e}	0.0037^{e}	0.0039^{e}	0.0039^{f}	0.0048^{g}
		16	0.0031^{e}	0.0028^{e}	0.0025^{f}	0.0026^{e}	0.0029^{f}	0.0034^{e}	0.0030^{g}	0.0035^{g}	0.0032^{i}
		24	0.0034^{e}	0.0028^{e}	0.0027^{f}	0.0027^{e}	0.0028^{f}	0.0032^{f}	0.0035^{e}	0.0032^{h}	0.0039^{h}
	17.3	8	0.0028^{f}	0.0024^{f}	0.0024^{f}	0.0024^{f}	0.0025^{g}	0.0026^{g}	0.0027^{g}	0.0029^{i}	0.0032^{i}
		16	0.0029^{f}	0.0023^{f}	0.0025^{f}	0.0026^{e}	0.0025^{g}	0.0027^{g}	0.0028^{g}	0.0029^{i}	0.0025^{k}
		24	0.0038^{e}	0.0031^{d}	0.0033^{e}	0.0034^{c}	0.0034^{e}	0.0038^{e}	0.0039^{e}	0.0033^{h}	0.0041^{h}
1.5	5.1	8	0.0070^{a}	0.0055^{a}	0.0048^{a}	0.0048^{a}	0.0049^{a}	0.0053^{c}	0.0060^{a}	0.0067^{b}	0.0075^{d}
		16	0.0051^{c}	0.0046^{b}	0.0047^{b}	0.0041^{b}	0.0048^{b}	0.0054^{b}	0.0051^{c}	0.0064^{c}	0.0118^{a}
		24	0.0047^{d}	0.0052^{b}	0.0043^{c}	0.0043^{b}	0.0047^{b}	0.0051^{c}	0.0059^{a}	0.0068^{b}	0.0063^{e}
	11.5	8	0.0031^{e}	0.0024^{f}	0.0020^{g}	0.0022^{f}	0.0024^{g}	0.0026^{h}	0.0028^{g}	0.0035^{g}	0.0035^{i}
		16	0.0026^{f}	0.0022^{f}	0.0021^{g}	0.0023^{f}	0.0030^{f}	0.0025^{h}	0.0026^{h}	0.0028^{j}	0.0054^{g}
		24	0.0024^{g}	0.0019^{h}	0.0016^{h}	0.0019^{h}	0.0019^{h}	0.0023^{i}	0.0023^{i}	0.0023^{j}	0.0022^{k}
	17.3	8	0.0028^{f}	0.0024^{f}	0.0022^{f}	0.0022^{f}	0.0022^{h}	0.0022^{i}	0.0022^{j}	0.0043^{e}	0.0030^{j}
		16	0.0028^{f}	0.0023^{f}	0.0022^{f}	0.0022^{f}	0.0020^{h}	0.0024^{h}	0.0022^{j}	0.0025^{j}	0.0048^{g}
		24	0.0024^{g}	0.0020^{g}	0.0018^{h}	0.0020^{g}	0.0018^{i}	0.0018^{j}	0.0019^{k}	0.0019^{k}	0.0019^{l}

Means in columns with different superscripts are significantly different at $P<0.05$

Effect of treatments on various grinding characteristics

The size reduction ratio and grinding effectiveness of fenugreek seed decreased from 4.11 to 1.61 (Table 2) and 0.0118 to 0.0018 with the increased level of moisture content, feed rate and grinder screen opening (Table 6). Size reduction ratio was found to be maximum at 8 kg h^{-1} feed rate, 1.5 mm hammer mill screen opening and 5.1% moisture content, respectively. The grinding effectiveness also found to be maximum for medium moisture content, medium feed rate and lower grinder

Table 7. Effect of moisture content and feed rate on grinding characteristics

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Screen opening (mm)					
		0.5		1.0		1.5	
		Bond's work index (kWh kg^{-1})	Kicks constant (kWh kg^{-1})	Bond's work index (kWh kg^{-1})	Kick's constant (kWh kg^{-1})	Bond's work index (kWh kg^{-1})	Kick's constant (kWh kg^{-1})
5.1	8	167.22^{e}	17.16^{d}	147.63^{e}	15.18^{d}	99.52^{f}	10.57^{f}
	16	77.74^{h}	7.540^{f}	67.14^{f}	6.83^{e}	31.32^{g}	3.23^{g}
	24	34.63^{i}	3.43^{g}	9.83^{i}	0.995^{g}	8.97^{h}	0.932^{h}
11.5	8	337.82^{b}	30.61^{b}	380.14^{b}	33.69^{b}	451.60^{b}	38.24^{b}
	16	150.18^{f}	13.37^{e}	187.86^{d}	16.55^{d}	170.44^{e}	14.36^{e}
	24	100.71^{g}	8.65^{f}	60.84^{g}	5.41^{f}	290.54^{c}	23.29^{c}
17.3	8	694.82^{a}	59.97^{a}	950.92^{a}	78.85^{a}	806.34^{a}	65.65^{a}
	16	248.47^{c}	21.02^{c}	247.46^{c}	20.89^{c}	262.89^{d}	21.47^{d}
	24	213.69^{d}	17.39^{d}	56.71^{h}	5.13^{f}	263.36^{d}	20.32^{d}

Means in columns with different superscripts are significantly different at $P<0.05$

Table 8. ANOVA to examine the effect of moisture content and feed rate on grinding characteristics

Screening opening (mm)		Sources	DF	MS	F_{cal}	P-value
0.5	Bonds work index	Feed rate	2	70196	6.378*	0.057
		Moisture content	2	66014	5.998**	0.063
		Feed rate × Moisture content	4	11005	-	-
	Kicks constant	Feed rate	2	590	7.811*	0.042
		Moisture content	2	424	5.617**	0.068
		Feed rate × Moisture content	4	75	-	-
1.0	Bonds work index	Feed rate	2	162210	3.595**	0.128
		Moisture content	2	89863	1.992**	0.251
		Feed rate × Moisture content	4	45118	-	-
	Kicks constant	Feed rate	2	1196	4.238**	0.103
		Moisture content	2	566	2.006**	0.249
		Feed rate × Moisture content	4	282	-	-
1.5	Bonds work index	Feed rate	2	79897	3.937**	0.114
		Moisture content	2	122019	6.012**	0.062
		Feed rate × Moisture content	4	20296	-	-
	Kicks constant	Feed rate	2	589	4.714**	0.088
		Moisture content	2	741	5.928**	0.063
		Feed rate × Moisture content	4	125	-	-

*Significant at 5%; **Non Significant

screen opening. Table 7 describes the effect of treatments on the various grinding characteristics such as Bond's work index, kicks constant, average particle size. It was observed that the Bond's work index and Kick's constant which are the measure of energy uptake decreased with the feed moisture level, feed rates with grinder screen opening. This was attributed to comparatively less grinding time taken to grind the unit feed with the increase of feed rate. Similar results were reported by Indira & Bhattacharya (2006) for grinding characteristics of different legumes and for microwave dried maize grains (Velu *et al.* 2006).

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 8). It was found that there exist a significant difference of Bond's work index and Kick's constants at 0.5 mm screen opening with feed rate while all other grinding characteristics were non-significant.

During swing type hammer mill grinding process, the Bond's work index and Kick's constant increased with the increase of moisture content, feed rate and grinder screen opening, respectively, whereas, the average particle, size reduction ratio and grinding effectiveness decreased. Since the specific energy was maximum for lesser screen opening (0.5 mm) and found decreased from 204.67 to 23.09 kJ kg^{-1} with increased feed rate and grinder screen openings (1.0 mm), it is concluded that for less energy consumption, the recommendable screen opening is 1.0 mm.

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