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Size reduction characteristics of black pepper

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Abstract

Black pepper corn at three moisture contents (5.5%, 11.4% & 17.6%, d.b.) was subjected to size reduction using micro pulverizer with screen aperture size (0.5 mm, 1.0 mm & 1.5 mm) and feed rate (8, 16 & 24 kg h^{-1}) at constant rotor speed (3000 rpm). It was found that the specific energy consumptions showed a decreasing trend (310.71–30.55 kJ kg^{-1}) with increase of feed rate but increasing trend with moisture content and screen openings. Maximum specific energy consumption was recorded for 11.4% moisture content and 8 kg h^{-1} feed rate with 1.0 mm screen aperture size. The average particle size increased from 0.21 mm to 0.29 mm with increase of moisture content and screen opening. The Bond's work index (0.086–0.312 kWh kg^{-1}) and Kick's constant (0.68 to 20.33 kWh kg^{-1}) showed direct motion with moisture content feed rate and screen aperture size. Size reduction ratio and grinding effectiveness of black pepper seed decreased from 25.42 to 14.57 and 0.077 to 0.008 with the increase in moisture content, feed rate and screen aperture size. The loose and compact bulk densities varied in the range of 322.8 to 1408 kgm^{-3} and 346.2 to 1760 kg m^{-3}, respectively for various mass fractions of sieve analysis. Bond's work index and Kick's constants were affected significantly ($P<0.05$) by moisture content but not feed rate for all screen aperture size.

Keywords: black pepper, particle size, sieve analysis, size reduction

Introduction

Black pepper (*Piper nigrum* L.) is the dried, mature but unripe berry (fruit) known for its pungent flavor. These are small dark brown or nearly black spherical fruits with a more or less regular and deep reticulate, wrinkled surface. Size reduction is primarily used for conservation of energy, increasing surface area, pore size of the material and number of contact points (Drzymala 1993; Ghorbani *et al.* 2010; Mani *et al.* 2004). Hammer mills are relatively cheap, easy to operate and suit wide range of particles. Energy consumption of grinding biomass depends on initial particle size, moisture content, material properties, material feed rate and machine variables (Walde *et al.*

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2002). Recently, several investigators (Anthony & Tabil 2006; Indira & Bhattacharya 2006; Goswami 2010) 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 the size reduction of coastal Bermuda grass with different moisture content and feed rate was studied by Balk (1964). The corn residues required more grinding energy than wheat straw and grain sorghum residues in a hammer mill at constant peripheral speed of 15.8 m s^{-1} (Von Bargen *et al.* 1981). Singh & Goswami (1999 & 2000) have studied the cryogenic grinding of cumin seed and cloves at different conditions and reported its influence on volatile oil content and its components, particle size distribution, volume mean diameter and specific energy consumption. Various grinding characteristics of raw and parboiled rice were evaluated (Sharma *et al.* 2008). Thus, the present work was carried out to study the size reduction characteristics of black pepper by differential sieve analysis.

Materials and methods

Materials preparation

Black pepper was procured from local market and cleaned manually by removing immature seeds and adhered foreign matter. The initial moisture content of black pepper was determined (AOAC 1995) and was found to be 11.4% d.b. For experimentation, predetermined quantity of black pepper was dried at 50°C air temperature in a recirculatory tray dryer (M/s Basic Technologies Pvt. Ltd., Kolkata) to achieve desired moisture content (Balasubramanian & Visvanathan 2011). To achieve higher moisture content (11.4% & 17.6% db), calculated amount of water was added and mixed (Murthy & Bhattacharya 1998). 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, % db – required moisture, % db) × 100] (1)

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

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

where, X=amount of water to be added, ml; Mo=initial moisture content, % d.b.; M_1=final moisture content, % d.b.; W_1=initial weight of the sample, g, and W_2=final weight of the sample, g.

Size reduction and differential sieve analysis

A micro pulverizer-hammer mill swing type (Osaw Agro Industies, Ambala, India) having a three-phase motor (3 HP, 3000 rpm) of 50-60 kg h^{-1} capacity was used for size reduction purpose. About 500 g sample in duplicate was ground using three different hammer screen aperture size (0.5 mm, 1.0 mm & 1.5 mm) and feed rate (8, 16 & 24 kg h^{-1}). The milling loss (%), moisture content and bulk density (loose and packed) of size reduced material was determined. For sieve analysis, a portion of ground sample was placed on the top of sieve set (1.201 mm, 0.894 mm, 0.5 mm, 0.401 mm, 0.295 mm, 0.251 mm, 0.177 mm, 0.157 mm & Pan) and shaken until it reached equilibrium. This was assessed by inspecting and weighing the samples at every 5 min intervals after an initial sieving time of 10 min. The material collected on each sieve was accurately weighed using a digital balance (TB-403, Denver Instruments, Bohemia, NY, LC: 0.001 g) and packed separately in zip loc polythene bags for further analysis.

Calculation of various parameters

Density (loose and packed) was determined for each sieve mass fraction (Singh *et al.* 2008). From the volume of one grain, diameter and surface area were calculated (Velu *et al.* 2006). All the calculated parameters are summarized below:

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

where, W_w and W_o are the power consumed by hammer mill at load and no load conditions, W; m is the feed rate, kg h^{-1}.

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

Grinding effectiveness = Surface area after size reduction/ Surface area before size reduction (5)

Weight of one particle = $(4/3)\ \pi\ (D_2/\ 2)^3\ p$ (6)

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

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

Based on 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 in kWh kg^{-1}) was calculated using 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) were calculated (Sahay & Singh 2001).

$$E = K_K \text{In}\ (D_1/\ D_2) \quad (10)$$

$$E = 0.3162\ W_2\ [(1/\ \sqrt{D_2}) - (1/\ \sqrt{D_1})] \quad (11)$$

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

Statistical analysis

Analysis of variance test (ANOVA) was carried out using AgRes, version 7.01 (Pascal International Software solutions, USA) and statistical procedures described by Gomez & Gomez (1984) to examine the effect of moisture content and feed rate ($P<0.05$) on size reduction characteristics.

Results and discussion

Physical characteristics of black pepper

The initial moisture content of black pepper was recorded as 11.4% d.b. The dimensions (major, medium and minor), geometric mean diameter, sphericity, surface area, thousand pepper corn weight and bulk density of seed conditioned at 5.5%, 11.4% & 17.6% moisture content varied from of 4.94 mm–5.28 mm, 4.63 mm–4.98 mm & 4.45 mm–4.80 mm, 4.67 mm–5.02 mm, 94.25%–94.75%, 68.52 mm^2–79.02 mm^2, 43.54 g–52.50 g & 555 kg m^{-3}–545 kg m^{-3}, respectively (Table 1).

Size reduction

Milling loss was found to be higher (124 g) at 5.5% moisture content and 24 kg h^{-1} feed rate in 0.5 mm grinding screen aperture size and decreased with the increase of moisture content as well as feed rate (Table 2). The loss at lower moisture content might be due the formation of more fine powdered material, which gets easily lost in the form of aerosol during the size reduction process. During the process, it was found that the temperature of grinder and product varied from 85°C–88°C and 77°C–80°C. Similar results were reported by Goswami & Singh (2003). Specific energy consumption with respect to various moisture content and feed rates with grinder screen aperture size is depicted in Table 3. It was found that the specific energy consumption decreased from 310.71 to 30.55 kJ kg^{-1} with increased feed rate (8–24 kg h^{-1}) and screen aperture size (0.5 mm–1.5 mm), respectively. It was noticed that the specific energy consumption showed maximum for samples ground at 11.4% moisture content and 8 kg h^{-1} feed rate with 0.5 mm screen aperture size (Table 3). On comparison there existed a significant difference ($P<0.05$) of specific energy consumption with each level of moisture content, feed rate and screen aperture size. The grinder equipped with smaller screen opening consumed more energy due to fine particles. Similar results were reported for alfalfa chops

Table 1. Physical characteristics of black pepper berry at various moisture contents

Moisture content (%, d.b.)	Major axis	Medium axis	Minor axis	Geometric mean diameter (mm)	Sphericity (%)	Surface area (mm^2)	Thousand berry weight (g)	Bulk density (kg m^{-3})
5.5	4.94	4.63	4.45	4.67	94.25	68.52	43.54	555
11.4	5.11	4.80	4.62	4.84	94.50	73.77	47.97	550
17.6	5.28	4.98	4.80	5.02	94.75	79.02	52.40	545

Table 2. Milling losses during grinding of black pepper berry at various moisture contents and feed rates

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Milling losses (g) Grinder screen opening (mm)		
		0.5	1.0	1.5
5.5	8	96.2^{d}	68.4^{g}	84.9^{c}
	16	119^{f}	115.1^{e}	120.7^{a}
	24	124.5^{g}	104.2^{g}	133.2^{c}
11.4	8	88.6^{b}	112^{f}	56.3^{e}
	16	92^{e}	129^{d}	147.8^{h}
	24	110.6^{g}	69.7^{b}	144^{b}
17.6	8	73.6^{a}	75.3^{b}	85.9^{f}
	16	72.8^{c}	53.6^{c}	82.8^{g}
	24	72.6^{g}	60.7^{a}	88.3^{d}

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

Table 3. Specific energy consumption for grinding of black pepper berry using hammer mill at various moisture contents and feed rates

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Specific energy consumption (kJ kg^{-1}) Grinder screen opening (mm)		
		0.5	1.0	1.5
5.5	8	117.39^{e}	221.46^{g}	262.16^{i}
	16	109.32^{c}	138.04^{f}	38.25^{b}
	24	104.30^{b}	49.04^{a}	30.55^{a}
11.4	8	189.23^{f}	310.71^{i}	220.14^{h}
	16	110.07^{c}	119.19^{d}	55.92^{c}
	24	97.80^{a}	73.13^{b}	92.03^{d}
17.6	8	243.16^{g}	187.46^{h}	168.98^{g}
	16	110.74^{d}	128.16^{e}	119.47^{f}
	24	104.23^{b}	91.78^{c}	104.92^{e}

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

(Ghorbani *et al.* 2010) and different biomass namely corn stover, switch grass, wheat and barley straw grind (Mani *et al.* 2004).

Percent fractions retained

The percent fractions retained by ground black pepper indicated that the maximum retention of materials was at 0.295 mm sieve size (Table 4). It has been observed that the average particle size was minimum at 0.5 mm screen aperture size and 8 kg h^{-1} feed rate. It is clear from the data that the moisture content of feed showed a linear relation with percent of medium size particles produced. However, feed rate showed a significantly positive effect in producing fine particles. This can be attributed to the higher friction produced due to sufficient filling of grinding cavity by increased feed rate. These results are in compliance with Jha & Verma (1999) for makhana and Fasina (2008) for peanut hull.

Gravimetric characteristics

Bulk density of the material was measured in the studied moisture range (5.5%–17.6%, d.b.). The loose and compact bulk density varied from 322.8 (11.4% d.b., moisture content at 24 kg h^{-1} feed rate and 1.5 mm aperture size) to 1408 kg m-3 (11.4% d.b., moisture content at 16 kg h^{-1} feed rate and 1.5 mm aperture size) & 346.2 (11.4% d.b., moisture content at 24 kg h^{-1} feed rate and 1.5 mm aperture size) to 1760 kg m^{-3}

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

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Mass fraction retained (%)								
		Sieve size (0.5 mm)								
		1.201	0.894	0.5	0.401	0.295	0.251	0.177	0.157	Pan
5.5	8	2.81^{d}	4.39^{c}	11.29^{b}	15.43^{d}	42.66^{f}	13.02^{f}	42.06^{d}	14.65^{g}	0.00
	16	2.97^{d}	7.24^{a}	10.34^{c}	25.85^{b}	51.22^{d}	19.09^{b}	3.76^{f}	31.73^{b}	0.00
	24	3.86^{e}	8.07^{b}	17.06^{a}	36.48^{a}	101.18^{a}	21.00^{a}	61.16^{b}	12.98^{h}	0.00
11.4	8	0.39^{b}	0.69^{g}	1.48^{e}	11.57^{f}	55.36^{d}	18.62^{c}	33.34^{e}	19.53^{e}	0.00
	16	0.60^{b}	1.58^{e}	4.67^{d}	19.20^{c}	58.72^{c}	17.92^{d}	1.56^{h}	45.87^{a}	0.00
	24	0.20^{a}	0.36^{h}	1.22^{e}	10.70^{f}	79.71^{b}	17.66^{d}	69.32^{a}	16.85^{f}	0.00
17.6	8	0.19^{a}	0.67^{g}	4.28^{d}	9.88^{g}	38.74^{g}	12.64^{e}	17.23^{g}	23.94^{d}	0.00
	16	0.75^{c}	2.14^{d}	9.75^{b}	24.02^{b}	54.07^{d}	19.08^{b}	54.12^{c}	26.28^{c}	0.00
	24	0.19^{a}	0.83^{f}	4.99^{d}	13.89^{e}	47.77^{e}	18.73^{c}	54.94^{c}	17.26^{f}	0.00
		Sieve size (1.0 mm)								
5.5	8	1.88^{a}	4.27^{a}	5.77^{a}	16.19^{c}	61.10^{e}	20.69^{b}	95.92^{a}	18.96^{g}	0.00
	16	0.63^{d}	1.46^{b}	2.97^{c}	10.56^{e}	51.11^{f}	17.99^{d}	95.96^{a}	22.09^{d}	0.00
	24	0.81^{c}	1.42^{b}	2.59^{d}	9.91^{f}	62.02^{e}	22.42^{a}	80.12^{b}	22.19^{c}	0.00
11.4	8	1.04^{b}	0.55^{c}	2.51^{d}	9.53^{f}	69.10^{d}	19.73^{c}	77.24^{d}	19.23^{f}	0.00
	16	1.07^{b}	0.56^{c}	0.81^{g}	5.64^{h}	40.60^{g}	17.72^{d}	78.30^{c}	23.07^{b}	0.00
	24	1.14^{c}	0.50^{d}	0.71^{h}	7.12^{g}	60.64^{e}	14.09^{f}	78.39^{c}	25.62^{a}	0.00
17.6	8	0.19^{e}	1.98^{b}	5.39^{b}	18.08^{b}	116.92^{a}	8.93^{g}	59.64^{f}	18.74^{g}	0.00
	16	1.08^{b}	0.31^{f}	0.94^{f}	15.47^{d}	76.95^{c}	17.89^{d}	67.98^{e}	23.50^{b}	0.00
	24	0.18^{e}	0.48^{e}	2.06^{e}	20.81^{a}	95.33^{b}	15.92^{e}	67.29^{e}	20.15^{e}	0.00
		Sieve size (1.5 mm)								
5.5	8	0.58^{d}	2.36^{a}	3.91^{e}	14.72^{f}	57.80^{h}	18.38^{c}	75.46^{d}	23.91^{a}	0.00
	16	0.43^{e}	1.69^{b}	4.33^{d}	13.51^{g}	62.17^{g}	17.01^{d}	89.03^{a}	24.75^{a}	0.00
	24	0.46^{e}	0.80^{c}	3.07^{f}	15.22^{e}	80.93^{d}	15.37^{e}	87.48^{b}	19.49^{e}	0.00
11.4	8	0.90^{b}	0.47^{e}	4.04^{c}	20.89^{d}	88.97^{c}	43.74^{a}	75.85^{d}	14.65^{f}	0.00
	16	0.46^{e}	0.20^{f}	3.09^{f}	12.16^{h}	102.46^{b}	9.36^{g}	69.32^{e}	21.75^{d}	0.00
	24	2.62^{a}	0.57^{d}	2.62^{g}	14.44^{f}	109.94^{a}	11.93^{f}	87.61^{b}	14.68^{f}	0.00
17.6	8	0.19^{g}	0.51^{d}	5.39^{b}	29.87^{a}	71.20^{f}	16.97^{d}	65.47^{f}	22.49^{b}	0.00
	16	0.79^{c}	0.17^{g}	5.81^{a}	21.84^{c}	75.33^{e}	19.73^{b}	82.38^{c}	21.71^{c}	0.00
	24	0.40^{f}	0.52^{d}	3.56^{f}	26.69^{b}	76.72^{e}	19.43^{b}	75.43^{d}	21.63^{c}	0.00

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

(17.2% d.b., moisture content at 24 kg h^{-1} feed rate and 1.5 mm aperture size), respectively (Tables 5 & 6). The compact bulk density showed a maximum value (1408 and 1760 kg m^{-3}) as compared to loose bulk density (322.8 and 346.2 kg m^{-3}) within the same particle range. It was also found that the loose and compact bulk densities were maximum at lower moisture content and small at screen aperture size with lower feed rate. Similar observations for buckwheat seed milling fractions were reported (Steadman *et al.* 2001).

Effect of treatments on various grinding characteristics

Size reduction ratio and grinding effectiveness of black pepper decreased from 25.42 to 14.57 & 0.0773 to 0.0080 with increase in moisture content, feed rate and screen aperture size

Table 5. The loose bulk density on various sieves after differential sieve analysis of black pepper berry in hammer mill

Moisture content (%, d.b.)	Feed rate ($kg\ h^{-1}$)	Loose bulk density ($kg\ m^{-3}$)								
		Sieve size (0.5 mm)								
		1.201	0.894	0.5	0.401	0.295	0.251	0.177	0.157	Pan
5.5	8	536.7^{f}	519.0^{d}	506.0^{d}	445.8^{c}	440.0^{d}	460.0^{b}	440.0^{d}	460.0^{b}	440.0^{c}
	16	1020.0^{a}	512.5^{e}	524.0^{c}	450.2^{b}	497.6^{a}	463.0^{a}	446.0^{c}	452.2^{c}	473.2^{a}
	24	410.0^{g}	410.0^{h}	406.0^{f}	362.0^{h}	366.4^{g}	392.8^{g}	388.0^{f}	394.0^{e}	446.0^{b}
11.4	8	559.0^{e}	588.0^{b}	582.0^{a}	420.0^{e}	458.0^{b}	458.0^{c}	454.0^{b}	456.0^{c}	391.8^{f}
	16	606.7^{d}	475.0^{f}	510.0^{d}	436.4^{d}	406.8^{f}	451.0^{d}	469.0^{a}	532.0^{a}	411.6^{d}
	24	490.0^{g}	388.0^{i}	390.8^{g}	358.0^{i}	352.2^{h}	374.2^{h}	388.8^{f}	384.0^{f}	413.8^{d}
17.6	8	566.0^{e}	539.0^{c}	480.0^{e}	408.0^{f}	440.8^{d}	441.8^{f}	442.0^{e}	394.0^{e}	414.0^{d}
	16	780.0^{c}	845.7^{a}	558.0^{b}	464.6^{a}	448.4^{c}	447.4^{e}	445.0^{c}	436.6^{d}	405.0^{e}
	24	900.0^{b}	436.3^{g}	490.0^{e}	394.8^{g}	411.4^{e}	386.0^{h}	410.4^{e}	383.8^{f}	403.6^{e}
		Sieve size (1.0 mm)								
5.5	8	549.0^{i}	590.0^{e}	516.0^{g}	490.2^{c}	495.2^{a}	450.0^{c}	428.6^{f}	406.2^{d}	397.0^{d}
	16	560.0^{h}	573.3^{f}	688.0^{b}	504.0^{b}	461.6^{d}	444.2^{d}	439.6^{c}	441.0^{a}	426.8^{a}
	24	664.0^{f}	382.0^{i}	464.0^{h}	356.6^{g}	392.4^{g}	400.6^{e}	425.0^{e}	415.0^{c}	413.4^{c}
11.4	8	645.0^{g}	597.0^{d}	564.0^{e}	459.6^{e}	475.0^{b}	458.6^{a}	443.2^{b}	420.6^{b}	395.8^{f}
	16	1400.0^{b}	710.0^{b}	810.0^{a}	532.0^{a}	451.0^{e}	455.8^{b}	454.2^{a}	441.4^{a}	417.8^{b}
	24	1300.0^{d}	436.7^{g}	473.0^{i}	353.4^{h}	354.6^{i}	394.0^{f}	371.4^{h}	386.2^{g}	413.8^{c}
17.6	8	1375.0^{c}	638.3^{c}	616.0^{d}	489.8^{d}	470.0^{c}	445.4^{d}	422.2^{e}	388.4^{f}	387.6^{g}
	16	672.5^{e}	1400.0^{a}	736.0^{b}	488.6^{d}	439.0^{f}	456.6^{b}	433.0^{d}	399.4^{e}	398.6^{e}
	24	1425.0^{a}	410.6^{h}	530.0^{f}	387.2^{f}	385.0^{h}	392.0^{g}	388.4^{g}	388.0^{f}	381.6^{h}
		Sieve size (1.5 mm)								
5.5	8	632.5^{f}	577.0^{e}	606.5^{d}	535.6^{a}	475.8^{c}	477.6^{b}	438.2^{c}	406.6^{d}	404.2^{e}
	16	460.0^{g}	591.4^{d}	588.0^{f}	510.2^{c}	457.0^{f}	436.8^{g}	417.4^{d}	421.6^{b}	371.0^{f}
	24	395.0^{i}	315.7^{g}	361.6^{h}	321.0^{g}	365.0^{h}	367.4^{f}	361.8^{f}	392.6^{f}	441.2^{a}
11.4	8	750.0^{e}	628.0^{c}	632.5^{c}	*508.0^{c}*	463.8^{d}	465.4^{c}	439.8^{c}	404.2^{d}	402.6^{e}
	16	860.0^{b}	1408.0^{a}	687.5^{b}	527.4^{b}	461.0^{e}	508.8^{a}	450.4^{a}	423.2^{a}	439.6^{b}
	24	820.0^{d}	315.0^{g}	332.6^{i}	337.2^{f}	322.8^{i}	346.8^{h}	358.6^{g}	393.6^{f}	408.4^{d}
17.6	8	836.0^{c}	592.9^{d}	597.0^{e}	503.2^{d}	478.2^{b}	463.0^{d}	439.2^{c}	405.6^{d}	405.6^{e}
	16	430.0^{h}	675.0^{b}	724.0^{a}	502.0^{d}	490.0^{a}	452.2^{e}	444.8^{b}	416.0^{c}	413.6^{c}
	24	1360.0^{a}	497.8^{f}	448.0^{g}	383.8^{e}	367.2^{g}	400.4^{g}	372.2^{e}	399.0^{e}	405.0^{e}

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

(Tables 7 & 8). Size reduction ratio was found to be maximum at 8 $kg\ h^{-1}$ feed rate, 0.5mm screen aperture size and 5.7% moisture content, respectively. Similarly, grinding effectiveness was also found to be maximum at lower moisture content, feed rate and screen aperture size. Table 9 describes the effect of treatments on various grinding characteristics such as Bond's work index, Kick's constant, average particle size and surface area. It was observed that the Bond's work index and Kick's constant which are measures of energy uptake increased with moisture level, feed rates and screen aperture size. This might be attributed to the comparatively less grinding time taken to grind the unit feed with increased feed rate. Similar results were reported by Indira & Bhattacharya (2006) for grinding characteristics of different

Table 6. The compact bulk density on various sieves after differential sieve analysis of black pepper berry

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Compact bulk density (kg m^{-3})								
		Sieve size (0.5 mm)								
		1.201	0.894	0.5	0.401	0.295	0.251	0.177	0.157	Pan
5.7	8	608.3^{g}	589.0^{e}	560.7^{e}	477.2^{d}	500.0^{a}	520.0^{a}	500.0^{f}	500.0^{f}	500.0^{g}
	16	1140.0^{a}	1322.5^{a}	610.0^{c}	507.8^{a}	412.4^{g}	516.8^{b}	516.2^{d}	536.6^{c}	580.6^{a}
	24	490.0^{i}	531.7^{g}	487.0^{h}	400.0^{i}	416.4^{f}	451.8^{f}	448.0^{g}	471.8^{i}	544.2^{b}
11.4	8	638.0^{f}	634.0^{b}	626.0^{a}	480.0^{c}	482.0^{c}	494.0^{e}	510.0^{e}	524.0^{d}	526.0^{d}
	16	705.0^{d}	577.0^{f}	556.0^{f}	457.8^{f}	453.8^{e}	510.2^{c}	527.8^{c}	580.6^{a}	515.6^{e}
	24	545.0^{h}	440.0^{i}	442.6^{i}	402.0^{h}	397.2^{h}	425.6^{h}	477.0^{f}	495.0^{g}	511.0^{f}
17.2	8	640.0^{e}	615.0^{c}	516.0^{g}	468.0^{e}	500.0^{a}	503.0^{d}	534.0^{a}	506.0^{e}	512.0^{f}
	16	804.0^{c}	600.0^{d}	616.0^{b}	489.2^{b}	494.4^{b}	497.2^{e}	533.0^{b}	541.2^{b}	533.0^{c}
	24	1025.0^{b}	520.0^{h}	600.0^{d}	430.2^{g}	462.8^{d}	443.6^{g}	476.4^{f}	476.4^{h}	489.0^{h}
		Sieve size (1.0 mm)								
5.7	8	624.0^{g}	670.0^{d}	551.2^{g}	528.2^{c}	533.6^{a}	507.6^{c}	526.8^{d}	536.8^{c}	525.2^{c}
	16	648.0^{f}	673.3^{c}	725.0^{c}	544.4^{b}	511.2^{b}	508.4^{c}	537.6^{a}	551.0^{a}	532.2^{b}
	24	730.0^{d}	427.0^{h}	526.0^{h}	392.8^{g}	449.6^{f}	443.0^{f}	490.2^{f}	532.2^{d}	532.6^{b}
11.4	8	742.5^{c}	674.0^{c}	672.0^{d}	490.0^{e}	498.2^{e}	520.6^{a}	530.0^{c}	526.8^{e}	521.2^{d}
	16	1450.0^{a}	780.0^{b}	863.3^{a}	570.8^{a}	500.8^{d}	513.2^{b}	535.4^{b}	544.4^{b}	550.2^{a}
	24	1360.0^{b}	553.3^{f}	498.0^{i}	392.8^{g}	392.4^{h}	457.8^{e}	472.2^{h}	501.6^{f}	528.6^{c}
17.2	8	700.0^{e}	666.1^{e}	669.0^{e}	525.8^{d}	511.4^{b}	520.4^{a}	522.6^{e}	497.8^{g}	502.2^{e}
	16	731.3^{d}	1500.0^{a}	784.0^{b}	524.6^{d}	504.8^{c}	509.6^{c}	521.2^{e}	527.6^{e}	520.0^{d}
	24	450.0^{h}	458.8^{g}	564.0^{f}	412.2^{f}	422.4^{g}	462.4^{c}	484.2^{g}	492.8^{h}	495.0^{f}
		Sieve size (1.5 mm)								
5.7	8	790.0^{g}	619.0^{f}	656.5^{d}	564.6^{a}	523.0^{b}	530.4^{c}	534.8^{b}	524.6^{d}	529.0^{d}
	16	680.0^{h}	624.3^{e}	624.5^{e}	544.8^{d}	518.8^{c}	534.0^{b}	532.6^{c}	546.4^{b}	470.0^{h}
	24	845.0^{f}	384.3^{i}	405.0^{g}	347.4^{i}	396.0^{g}	413.6^{h}	427.0^{g}	509.4^{h}	514.0^{g}
11.4	8	1000.0^{c}	654.0^{d}	662.5^{c}	558.2^{b}	509.2^{e}	517.2^{e}	535.8^{b}	525.0^{e}	526.8^{e}
	16	950.0^{d}	1508.0^{a}	715.0^{b}	552.6^{c}	513.0^{d}	560.6^{a}	524.6^{d}	559.6^{a}	563.6^{a}
	24	1380.0^{b}	386.3^{h}	346.2^{h}	359.8^{h}	359.2^{h}	393.0^{i}	454.0^{e}	522.0^{f}	535.2^{c}
17.2	8	944.0^{e}	663.5^{c}	662.0^{c}	521.8^{f}	540.0^{a}	523.2^{d}	544.6^{a}	526.6^{e}	515.4^{f}
	16	451.7^{i}	745.0^{b}	758.0^{a}	529.6^{e}	519.2^{c}	493.6^{f}	535.0^{b}	541.6^{c}	536.8^{b}
	24	1760.0^{a}	606.7^{g}	537.0^{f}	413.6^{g}	403.6^{f}	424.6^{g}	465.4^{f}	513.6^{g}	534.2^{c}

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

Table 7. Effect of moisture content and feed rate on size reduction ratio of black pepper berry

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Size reduction ratio		
		Sieve size (mm)		
		0.5	1.0	1.5
5.5	8	20.88^{d}	16.35^{a}	17.82^{e}
	16	20.51^{d}	17.51^{c}	16.97^{c}
	24	14.57^{a}	17.58^{c}	16.45^{c}
11.4	8	22.05^{f}	18.40^{d}	15.72^{a}
	16	21.43^{e}	20.28^{f}	17.30^{d}
	24	18.57^{b}	19.03^{e}	15.97^{b}
17.6	8	25.42^{g}	17.36^{b}	18.35^{f}
	16	19.64^{c}	18.81^{d}	17.47^{d}
	24	21.68^{e}	17.78^{c}	17.66^{e}

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

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

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Grinding effectiveness								
		Sieve size (0.5 mm)								
		1.201	0.894	0.5	0.401	0.295	0.251	0.177	0.157	Pan
5.7	8	0.0117^{b}	0.0121^{b}	0.0127^{b}	0.0150^{b}	0.0143^{c}	0.0137^{e}	0.0143^{c}	0.0143^{b}	0.0143^{a}
	16	0.0039^{g}	0.0106^{d}	0.0107^{f}	0.0108^{f}	0.0141^{d}	0.0140^{d}	0.0137^{e}	0.0132^{d}	0.0129^{d}
	24	0.0071^{e}	0.0074^{e}	0.0088^{g}	0.0097^{g}	0.0091^{e}	0.0090^{g}	0.0085^{i}	0.0090^{f}	0.0088^{g}
11.4	8	0.0066^{f}	0.0057^{f}	0.0123^{c}	0.0148^{c}	0.0182^{b}	0.0145^{c}	0.0145^{b}	0.0140^{c}	0.0129^{d}
	16	0.0090^{d}	0.0111^{c}	0.0115^{d}	0.0139^{d}	0.0141^{d}	0.0125^{f}	0.0121^{f}	0.0110^{e}	0.0124^{e}
	24	0.0007^{h}	0.0010^{g}	0.0009^{h}	0.0012^{h}	0.0012^{f}	0.0012^{h}	0.0011^{h}	0.0011^{g}	0.0011^{h}
17.2	8	0.0185^{a}	0.0171^{a}	0.0186^{a}	0.0227^{a}	0.0218^{a}	0.0201^{a}	0.0203^{a}	0.0192^{a}	0.0167^{b}
	16	0.0098^{c}	0.0121^{b}	0.0120^{c}	0.0133^{e}	0.0134^{e}	0.0125^{f}	0.0112^{g}	0.0108^{e}	0.0104^{f}
	24	0.0064^{f}	0.0127^{b}	0.0110^{e}	0.0154^{b}	0.0143^{c}	0.0149^{b}	0.0139^{d}	0.0139^{c}	0.0135^{c}
		Sieve size (1.0 mm)								
5.7	8	0.0071^{d}	0.0066^{f}	0.0080^{d}	0.0084^{h}	0.0083^{h}	0.0087^{g}	0.0084^{g}	0.0082^{h}	0.0084^{h}
	16	0.0072^{d}	0.0079^{e}	0.0080^{d}	0.0109^{e}	0.0107^{f}	0.0103^{f}	0.0101^{e}	0.0102^{c}	0.0103^{c}
	24	0.0076^{c}	0.0080^{e}	0.0079^{d}	0.0101^{g}	0.0104^{g}	0.0102^{f}	0.0101^{e}	0.0106^{b}	0.0105^{b}
11.4	8	0.0088^{b}	0.0085^{d}	0.0079^{d}	0.0105^{f}	0.0112^{c}	0.0113^{b}	0.0107^{b}	0.0104^{d}	0.0108^{d}
	16	0.0046^{f}	0.0085^{d}	0.0077^{e}	0.0117^{c}	0.0133^{a}	0.0130^{a}	0.0124^{a}	0.0122^{a}	0.0121^{a}
	24	0.0073^{d}	0.0035^{g}	0.0068^{f}	0.0101^{g}	0.0105^{e}	0.0104^{e}	0.0102^{d}	0.0101^{c}	0.0102^{c}
17.2	8	0.0065^{e}	0.0112^{a}	0.0091^{b}	0.0121^{b}	0.0106^{e}	0.0108^{c}	0.0097^{f}	0.0090^{g}	0.0089^{g}
	16	0.0036^{g}	0.0088^{c}	0.0098^{a}	0.0124^{a}	0.0124^{b}	0.0106^{d}	0.0103^{c}	0.0097^{e}	0.0092^{f}
	24	0.0104^{a}	0.0102^{b}	0.0083^{c}	0.0114^{d}	0.0111^{d}	0.0102^{f}	0.0097^{f}	0.0095^{f}	0.0095^{e}
		Sieve size (1.5 mm)								
5.7	8	0.0064^{b}	0.0082^{c}	0.0077^{g}	0.0090^{g}	0.0097^{f}	0.0096^{f}	0.0095^{f}	0.0097^{c}	0.0096^{d}
	16	0.0052^{e}	0.0080^{d}	0.0079^{f}	0.0094^{f}	0.0103^{e}	0.0101^{e}	0.0098^{e}	0.0100^{b}	0.0100^{c}
	24	0.0058^{d}	0.0083^{c}	0.0083^{d}	0.0106^{d}	0.0102^{e}	0.0105^{c}	0.0101^{d}	0.0105^{a}	0.0107^{a}
11.4	8	0.0060^{c}	0.0066^{f}	0.0066^{h}	0.0075^{h}	0.0079^{g}	0.0077^{g}	0.0077^{g}	0.0075^{e}	0.0087^{g}
	16	0.0061^{c}	0.0039^{g}	0.0081^{e}	0.0105^{d}	0.0114^{d}	0.0104^{d}	0.0111^{b}	0.0104^{a}	0.0103^{b}
	24	0.0112^{a}	0.0068^{e}	0.0067^{h}	0.0096^{e}	0.0098^{f}	0.0103^{d}	0.0095^{f}	0.0094^{d}	0.0094^{e}
17.2	8	0.0061^{c}	0.0133^{a}	0.0126^{b}	0.0147^{a}	0.0129^{c}	0.0124^{a}	0.0120^{a}	0.0100^{b}	0.0100^{c}
	16	0.0035^{f}	0.0126^{b}	0.0141^{a}	0.0136^{b}	0.0136^{a}	0.0124^{a}	0.0107^{c}	0.0093^{d}	0.0091^{f}
	24	0.0028^{g}	0.0082^{c}	0.0092^{c}	0.0120^{c}	0.0123^{b}	0.0117^{b}	0.0106^{c}	0.0096^{c}	0.0093^{e}

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

Table 9. Effect of moisture content and feed rate on milling characteristics of black pepper berry

Moisture content (%, d.b.)	Feed rate (kg h^{-1})	Sieve size (mm)					
		0.5		1.0		1.5	
		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})	Bond's work index (kWh kg^{-1})	Kick's constant (kWh kg^{-1})
5.5	8	0.2097^{i}	6.93^{g}	0.3119^{g}	16.91^{g}	0.2757^{e}	3.45^{f}
	16	0.1095^{d}	3.31^{d}	0.1320^{d}	7.56^{e}	0.1343^{d}	1.32^{b}
	24	0.1016^{c}	2.61^{c}	0.0888^{a}	3.16^{c}	0.0858^{a}	0.68^{a}
11.4	8	0.2001^{h}	10.85^{h}	0.2467^{e}	20.30^{h}	0.3293^{f}	17.45^{i}
	16	0.1133^{e}	3.41^{e}	0.1096^{c}	3.61^{c}	0.1218^{c}	1.81^{c}
	24	0.0814^{b}	2.12^{b}	0.0876^{a}	1.66^{a}	0.0910^{b}	2.14^{d}
17.6	8	0.1715^{g}	12.71^{i}	0.2833^{f}	13.41^{f}	0.2669^{e}	11.62^{h}
	16	0.1290^{f}	3.72^{f}	0.1393^{d}	4.53^{d}	0.1389^{d}	4.22^{g}
	24	0.0724^{a}	2.09^{a}	0.0956^{b}	2.21^{b}	0.0915^{b}	2.45^{e}

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

legumes and for microwave dried maize grains (Velu *et al.* 2006).

Analysis of variance

ANOVA was carried out to examine the effect of moisture content, feed rate and screen aperture size on various size reduction characteristics *viz.*, Bond's work index, Kick's constant (Table 10). There existed a significant difference among all the size reduction characteristics. The Kick's constant varied significantly with feed rate, except moisture content for all screen aperture size.

Thus, the study indicated that the specific energy was maximum for lesser screen aperture size (0.5 mm) and decreased from 310.71 to 30.55 kJ kg^{-1} with increased feed rate and screen aperture size. Average particle size increased from 0.2095 mm to 0.2940 mm and Bond's work index and Kick's constant also increased from 0.0858 to 0.3119 kWh kg^{-1}, 0.68 to 20.33 kWh kg^{-1} with the increase in moisture content (5.5%–17.6% d.b.), feed rate (8-24 kg h^{-1}) and screen aperture size (0.5 mm–1.5 mm), respectively. Bond's work index and Kick's constant showed significant effect on feed rate and moisture content on all screen aperture sizes except moisture content at 0.5 mm.

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Table 10. ANOVA to examine the effect of moisture content and feed rate on milling characteristics of black pepper berry

Sieve size (mm)	Indices/ constants	Sources	DF	MS	F_{cal}	P Value
0.5	Bond's work index	Moisture content	2	0.009	35.050*	0.003
	(KWh kg^{-1})	Feed rate	2	0.000	0.721 ^{NS}	0.540
		Moisture content × Feed rate	4	0.000		
	Kick's constant	Moisture content	2	54.163	17.700*	0.010
	(KWh kg^{-1})	Feed rate	2	2.741	0.896 ^{NS}	0.477
		Moisture content × Feed rate	4	3.060		
1.0	Bond's work index	Moisture content	2	0.031	107.192*	0.000
	(KWh kg^{-1})	Feed rate	2	0.001	2.664^{NS}	0.184
		Moisture content × Feed rate	4	0.000		
	Kick's constant	Moisture content	2	177.508	30.231*	0.004
	(KWh kg^{-1})	Feed rate	2	4.972	0.847 ^{NS}	0.494
		Moisture content × Feed rate	4	5.872		
1.5	Bond's work index	Moisture content	2	0.034	67.555*	0.001
	(KWh kg^{-1})	Feed rate	2	0.000	0.462^{NS}	0.660
		Moisture content × Feed rate	4	0.000		
	Kick's constant	Moisture content	2	76.647	5.297*	0.075
	(KWh kg^{-1})	Feed rate	2	23.829	1.647^{NS}	0.301
		Moisture content × Feed rate	4	14.469		

*Significant at $p<0.05$; F tab(df2,2)=6.94; NS=non significant

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