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Effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed (*Cuminum cyminum* Linn.) under quasi-static loading

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Abstract

Force and deformation curve of agricultural material must be provided for proper design of harvesting, processing machineries. In this research, fracture resistance of whole cumin seed was measured in terms of average compressive force, seed rupture force and energy absorbed. In this study 10 treatments were performed as randomized complete block design with 20 replications. Cumin seeds were quasi-statically loaded in horizontal and vertical orientations with moisture contents in three levels: 5.7%, 9.5%, and 15% seed size in three levels: small, medium, and large; loading rates in two levels: 2 and 5 mm/min; and two seed orientations: horizontal and vertical.

The results showed that the force required for initiating seed rupture decreased from 15.7 to 11.96 N and 58.2 to 28.8 N, and the energy absorbed at seed rupture increased from 1.8 to 8.6 mJ and 7.6 to 14.6 mJ, with increase in moisture content from 5.7% to 15% d.b., for vertical and horizontal orientations, respectively. This showed that seeds are more flexible in horizontal orientation. Rupture force requires less energy under vertical loading than horizontal loading. Maximum energy absorbed was found to be 15.3 mJ for small seed with 15% moisture content under horizontal loading. Minimum energy observed was 1.73 mJ for large seed with 5.7% moisture content under vertical loading. The highest mechanical strength (60 N) is related to a small seed with a moisture content of 5.7% under horizontal loading and the lowest (10.8 N) is attributable to a large seed with a moisture content of 15% under vertical loading. Energy absorbed by the small seed at high moisture content increased in horizontal orientations of loading.

Keywords: Cumin seed; Energy; Rupture force; Quasi-static loading; Mechanical properties

1. Introduction

Cumin (*Cuminurn cyminum* Linn.) is an annual plant of the family Umbelliferae. Cumin seed is generally used as a food additive in the form of powder for imparting flavor to different food preparations. It also has a variety of medicinal properties. The cumin seeds contain 3–4% volatile oil and about 15% fixed oil (Spices Board Statistics, 2006). Cumin powder is an important ingredient in curry mixes and some bakery products. Volatile oil finds its use in perfumery and foods, especially in oriental dishes, as a flavourant.

Physical properties of cumin seeds are essential for the design of equipment for handling, harvesting, aeration, drying, storing, grinding and processing. These properties are affected by numerous factors such as size, form, and moisture content of the grain. Moreover, the knowledge of fracture characteristics of seed is imperative for a rational design of efficient grinding systems, as well as the optimization of the process and product parameters.

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Bilanski (1966) applied compressive loads at the rate of 1.27 mm/min to soybeans and measured the force, and work required to initiate seed coat rupture dropped from 57.8 N at 1% moisture (wet basis) to 44.4 N at 16% moisture for a soybean loaded in the horizontal hilum position. Average work increased from 3.8 mJ at 1% moisture to 31.5 mJ at 16% moisture. Prasad and Gupta (1973) studied the behavior of paddy grains under quasi-static compressive loading. It was reported that the maximum compressive strength of paddy grains ranged from 40.6 to 160.7 N in the moisture content range of 12–24% d.b. The values of maximum compressive strength of paddy grain decreased with increasing moisture content. The modulus of toughness varied from 3.96 to 30.87 mJ and was at a maximum between moisture contents of 14–16% d.b. Deformation at rupture was maximum at a moisture content of 15% d.b. Paulsen (1978) studied the compressive force, deformation, and toughness of soybean at seed coat rupture under compressive loading in the moisture range of 9–20% d.b. It was observed that force required for initiating seed coat rupture decreased as soybean moisture content increased from 9% to 20% d.b. Maximum toughness occurred in the moisture content range of 12–16% d.b., indicating an optimum moisture range for absorbing compressive energy. Soybeans loaded in the vertical hilum position required less energy for seed coat rupture than those in the horizontal position. Joshi (1993) observed that force required for initiating seed coat rupture of pumpkin seed increased as the moisture content increased from 5.1% to 10.5% d.b., beyond which it steadily decreased up to a moisture content of 21.7% d.b. It was also reported that deformation occurring at seed coat or kernel rupture increased as seed moisture content increased from 5.1% to 21.7% d.b. and it was substantially greater for the seed loaded in the vertical orientation than that in the horizontal orientation. Energy absorbed by the seed and kernel increased in both horizontal and vertical orientations of loading as the moisture content increased to 15% d.b. beyond this moisture content the energy absorbed declined.

Recently, rheological properties of several grains have been reported in the literature. According to Waananen and Okos (1988), failure stress of corn decreased, whereas failure strain increased with an increase in moisture content and temperature. The maximum compressive stress for wheat and canola decreased linearly with an increase in moisture content (Bargale et al., 1995). The stress, strain, modulus of deformability and energy to yield point were found to be a function of loading rate and moisture content for different varieties of wheat kernels (Kang et al., 1995). Some engineering properties of locust bean seed were investigated by Ogunjimi et al. (2002), who concluded that the seed orientation that gave the least resistance to cracking was along the thickness. The cracking force obtained in loading along the thickness lay between 154 and 204 N. Loading on the vertical axis gave the highest resistance to cracking. In a study, Isik and Unal (2007) observed that the shelling resistance of white speckled red kidney bean grain decreased as the moisture content increased from 98.26 to 53.67 N. Lately, a similar study was done by Altuntas and Karadag (2006) that the mechanical properties of sainfoin, grasspea, and bitter vetch seeds were determined in terms of average rupture force, specific deformation and rupture energy along *X*-, *Y*- and *Z*-axes. The mean values of rupture force, specific deformation and rupture energy for sainfoin seed were 7.40, 9.72 and 4.56 N; 8.94%, 1.71% and 9.97% and 1.97, 0.46 and 0.71 N mm for along *X*-, *Y*- and *Z*-axes, respectively. The mean values of rupture force, specific deformation and rupture energy for grasspea seed were 254.40, 42.60 and 100.80 N; 27.53%, 0.29% and 14.03%; and 187.20, 29.25 and 38.77 N mm for along *X*-, *Y*- and *Z*-axes, respectively. The mean values of rupture force, specific deformation and rupture energy for bitter vetch seed were 57.60, 45.00, 87.00 N; 7.60%, 1.62%, 1.93%; 10.14, 4.42, 0.86 N mm for along *X*-, *Y*- and *Z*-axes, respectively. Limited research has been conducted on the mechanical properties and fracture resistance of cumin seed. Some mechanical properties of cumin seed under compressive loading were studied by Singh and Goswami (1998). They reported that the rupture force increased with increasing deformation and decreasing moisture content in the horizontal and vertical orientations.

Objectives were to determine fracture behavior of cumin seed by examining the effect of moisture content, seed size, loading rate and seed orientation on rupture force and energy of cumin seed.

2. Materials and methods

Cumin seed, as shown in Fig. 1, was obtained from four regions of Khorasan province (one of the producer provinces in Iran, the cultivated area of which is 11,682 hectares with annual production of 5455 tonnes and yield of 467 kg/ha (Anon, 2006). The seeds were cleaned manually and foreign matters, broken and immature seeds were removed by hand. According to Singh and Goswami (1996, 1998), the seeds were sieved into three size categories (small, medium, and large) using 8, 10, and 12 mesh sieves as presented in

Fig. 1. Cumin seed together with two mericarps.

Table 1
Classification of cumin seed based on seed geometric mean diameter

Seed size	Seed length	Geometric mean diameter	Sphericity ratio
Small	2.1–2.5	2.27	0.35
Medium	2.6–3	2.81	0.37
Large	3.1–3.5	3.33	0.39

Table 1. To determine the average size of the seed, a sample of 100 seeds from each category was randomly selected. The three linear dimensions of the seeds, namely length (L), width (W) and thickness (T) were carefully measured using micrometer reading to 0.01 mm. The geometric mean diameter (GMD) and sphericity ratio were computed using the following equations (Mohsenin, 1986).

$$\mathrm{GMD} = (LWT)^{\frac{1}{3}} \qquad \text{Sphericity ratio} = \frac{\mathrm{GMD}}{L}$$

The initial moisture content of the cumin seed, prepared from regions' farmers, was determined through oven drying method to be 5.7%. To obtain seeds with different moisture contents, a fine spray of water was applied using a spray gun. The time of spray was varied to obtain seeds with different moisture contents. These seeds were kept in covered glass bottles, at 5 °C for 48 h with occasional gentle shaking to ensure uniform moisture distribution. The quantity of water which should be added to the seed was determined by the following equation (Murthy and Bhattacharya, 1998):

$$W_1(100 + M_1) = W_2(100 + M_0),$$

where M_0 is the initial moisture content (% dry basis), W_1 is denoted as the initial weight of the seeds at an initial moisture content of M_0 (g), and W_2 is defined as the final weight of the seeds at a moisture content W_1 (g).

In this study, 10 treatments were considered : moisture content in three levels: 5.7%, 9.5%, and 15%; seed size in three levels: small, medium, and large; loading rate in two levels: 2 and 5 mm/min; and seed orientation in two levels: horizontal and vertical. Experiments were performed as randomized complete block design with 20 replications.

Quasi-static compression tests were performed with an Instron Universal Testing Machine (Model QTS 25) equipped with a 25-kg compression load cell and integrator (Khazaei, 2002). The measurement accuracy was ±0.001 N in force and 0.001 mm in deformation. For each treatment twenty seeds were randomly selected and the average values of all the 20 tests were reported. The individual seed was loaded between two parallel plates of the machine and compressed at the preset condition until rupture occurred as is denoted by a bio-yield point in the force–deformation curve. The bio-yield point was detected by a break in the force–deformation curve. Once the bio-yield was detected, the loading was stopped. To determine the effect of the orientation of loading, the seed was positioned horizontally (Fig. 2a), with the major axis of the seed being normal to the direction of loading, or lengthwise. For vertical loading (Fig. 2b), the major axis of the seed was parallel to the direction of loading. The deformation (strain) was taken as the change in the original dimension of the seed. Note that load cell deflection under load was found to be negligible for loads used in this study.

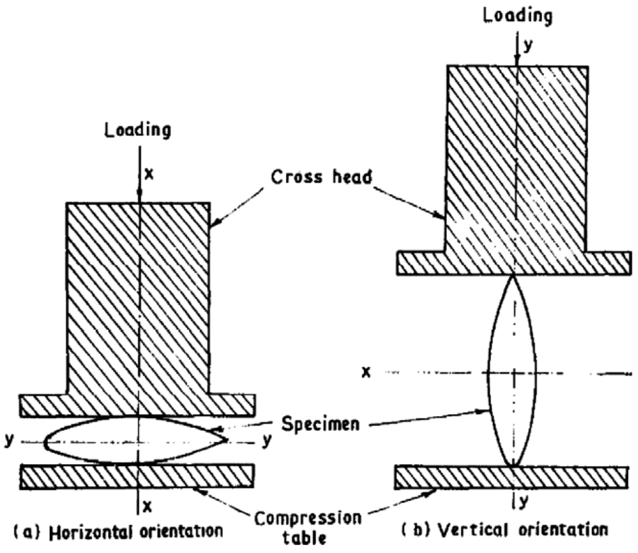

Fig. 2. Orientations of cumin seed under compressive loading.

The toughness of the seeds was expressed as the energy required for causing rupture (failure) in the compressed seed and was determined by calculating the area under the force–deformation curve up to seed rupture (Fig. 3). The latter procedure was done by the utilization of computing software installed on the apparatus used.

Statistical analysis was done on randomized complete block design applying the analysis of variance (ANOVA) using SPSS13 software. The F test was used to determine significant effects of each treatment, and Duncan's multiple ranges test was used to separate means at a 5% level of significance.

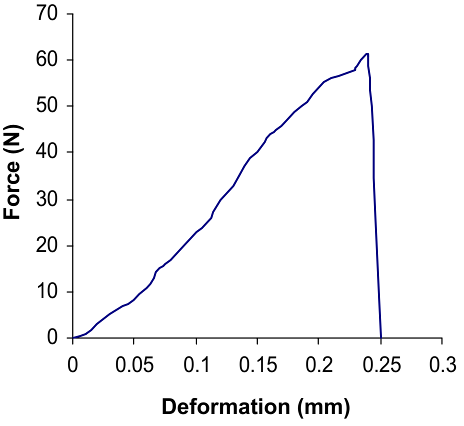

Fig. 3. Typical force–deformation characteristics of cumin seed.

Table 2
Analysis of the variance of parameters considered on rupture force and energy of cumin seed

Variation source	DF	Rupture force (N)	Rupture energy (mJ)
Treatment	35	6595.24[b]	478.421[b]
Seed size	2	262.681[b]	4.407[ns]
Loading rate	1	580.719[ns]	237.466[b]
Moisture content	2	16852.951[b]	2855.687[b]
Seed orientation	1	174095.212[b]	9497.91[b]
Seed size × loading rate	2	42.081[ns]	11.906[ns]
Seed size × moisture content	2	79.922[ns]	38.578[b]
Loading rate × moisture content	2	17.053[ns]	3.523[ns]
Seed size × seed orientation	2	19.021[ns]	65.679[b]
Loading rate × seed orientation	1	243.767[a]	36.522[a]
Moisture content × seed orientation	2	10294.365[b]	348.325[b]
Seed size × loading rate × moisture content	4	15.170[ns]	7.066[ns]
Seed size × loading rate × seed orientation	2	33.484[ns]	12.275[ns]
Seed size × moisture content × seed orientation	4	92.332[ns]	33.516[b]
Loading rate × moisture content × seed orientation	2	22.22[ns]	10.437[ns]
Seed size × loading rate × moisture content × seed orientation	4	19.072[ns]	7.932[ns]
Error	684	43.224	6.522

ns: Corresponding to no significant difference.
[a] Corresponding to confidence of interval, 95%.
[b] Corresponding to confidence of interval, 99%.

3. Results and discussion

Variance analysis of data, as was shown in Table 2, indicates that moisture content and seed orientation created a significant effect on rupture energy and force ($P < 0.01$). Seed size and loading rate also had a significant effect on rupture force and rupture energy, respectively. The average force to rupture the seed was obtained as 29.293 N varying from 7.349 to 85.347 N, while the average rupture energy of the seed was calculated as 8.246 mJ ranging from 0.196 to 25.997 mJ. According to Table 2, the interaction effects of moisture content × seed orientation and loading rate were not significant on rupture force. Based on the statistical analyses, interaction effects of seed size × moisture content, seed size × seed orientation, moisture content × seed orientation, seed size × moisture content × seed orientation were significant at 1% level but loading rate × seed orientation were significant at 5% level on rupture energy of the cumin seed.

In the following paragraphs, the effects of each factor on the rupture energy and force are comprehensively discussed.

3.1. Moisture content

Stepwise analysis of obtained data revealed that among three quantitative variables, namely moisture content, seed size, and loading rate, the dominant factor on the rupture force of the seed under quasi-static loading is moisture content. The force required for initiating seed rupture at different moisture content and seed size is shown in Fig. 4a. Rupture force decreased with an increase in seed moisture content. As given in Table 3, rupture force was 36.97 N at 5.7% moisture. This is significantly more than the force required to initiate seed rupture at 15% moisture (around 1.8 times). This may be due to the fact that at higher moisture content, the seed became softer and required less force. This conclusion was consistent with the findings of Konak

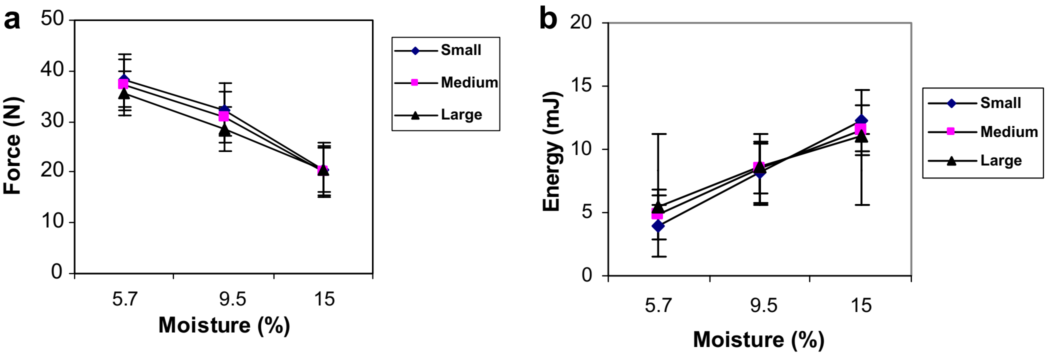

Fig. 4. Effect of moisture content and seed size on rupture force and energy.

Table 3
Mean comparison of rupture force and energy of cumin seed in different size categories and moisture content

Seed size (mm)	Rupture force (N)	Rupture energy (mJ)
2.1–2.5	30.298 a	8.097 a
2.6–3	29.371 ab	8.28 a
3.1–3.5	28.21 b	8.361 a
Moisture content (%)		
5.7	36.977 a	4.704 a
9.5	30.544 b	8.44 b
15	20.358 c	11.595 c

The means with minimum common letter are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test.

et al. (2002), who reported the highest rupture force of chick pea seeds was obtained as 210 N with a moisture content of 5.2% d.b. It was also stated that the seeds became more sensitive to cracking at a higher moisture content; hence, they required less force to rupture. Altuntas and Yildiz (2007) conducted a research to study the effect of moisture content on some physical and mechanical properties of faba bean grains(*Vicia faba* L.) grains and reported that as the moisture content increased from 9.89% to 25.08%, the rupture force values ranged from 314.17 to 185.10 N; 242.2 to 205.56 N and 551.43 to 548.75 N for X-, Y-, and Z-axes, respectively. There are conflicting reports on the effect of moisture content on rupture force. Paulsen (1978), Hoki and Tomita (1976), Liu et al. (1990) reported a decrease in rupture force values for soybean with an elevation in moisture content, which was true for the present work too. On the other hand, the compressive strength for snap bean (*Phaseohs vulguris* L.) was reported to increase with elevation in moisture content (Bay et al., 1996).

Energy absorbed at seed rupture increased from 4.7 to 11.6 mJ with the increasing moisture content from 5.7% to 15% d.b. Energy absorbed at seed rupture was a function of both force and deformation up to rupture point. At low moisture content, the seed requires high force to be ruptured and its deformation was low but at high moisture content, the rupture force was low and the deformation was high. This fact showed that energy absorbed at seed rupture increases as the moisture content of the seed increases indicating high resistance to seed rupture during compressive loading. The latter result has been documented by Khazaei (2002), who investigated energy absorbed in pea rupture under quasi-statistically loading and reported that with an increase in seed moisture content, the energy absorbed increases significantly. This attribute caused the broken seed percentage to be reduced during dynamic loading (Kirk and Mcleod, 1967).

3.2. Seed size

There was significant difference between small and large seed size ($P < 0.05$) as shown in Table 3. The force required to initiate seed rupture increased as seed size increased so that the average rupture force of small seeds was about 1.4-fold of that of large ones. Investigating the interaction effect of moisture content and seed size on rupture force showed that most difference among size categories was found at 5.7% moisture. Size had no effect on force required at 15% moisture content. Energy absorbed at seed rupture at the 15% moisture level decreased as the seed size increased among horizontal orientation (Fig. 5) but that is contrary to what was observed at 15% moisture in which an increase in seed size was responsible for an increase in rupture energy (Fig. 4). This may be attributed to the fact that an increase of moisture content in the seed can cause the modulus of elasticity to be increased and the large seeds to be capable of being more deformable under compressive loading and subsequently yielding an increase in rupture energy.

3.3. Seed orientation

Considering the values presented in Tables 4 and 5 and Fig. 5, the seeds were more flexible in the horizontal loading direction, and the rupture under vertical loading direction requires less energy than that under horizontal loading. This is possibly due to the fact that under vertical loading, smaller contact area of the seed with the compressing plates results in the expansion of high stress in the cumin seed.

The most and the least difference in rupture force value between vertical and horizontal loading were found to be at 15% and 5.7% moisture, respectively, as shown in Fig. 5a. Rupture energy also was a function of seed orientation so that energy absorbed at seed rupture under horizontal

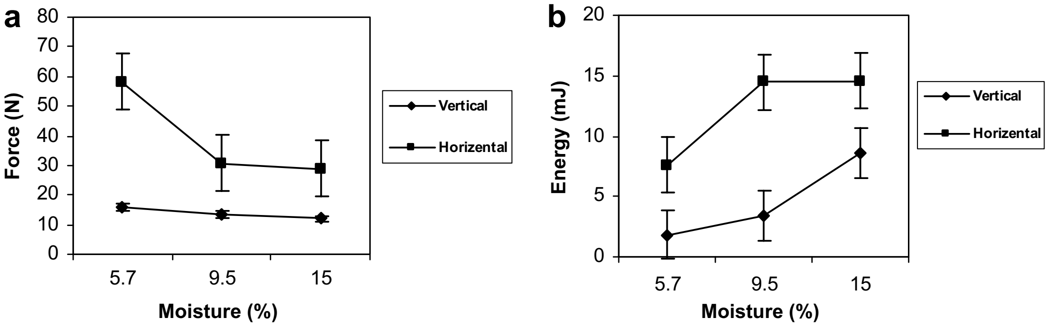

Fig. 5. Interaction effect of moisture content and seed orientation on force and energy required to initiate seed rupture.

Table 4
Mean comparison of rupture force and energy of cumin seed considering interaction effect of seed size and seed orientation

Seed size (mm)	Seed orientation			
	Rupture force (N)		Rupture energy (mJ)	
	Vertical	Horizontal	Vertical	Horizontal
2.1–2.5	14.427 a	46.168 b	5.033 a	11.16 b
2.6–3	14.028 a	44.714 b	4.541 a	12.02 bc
3.1–3.5	12.774 a	43.645 b	4.268 a	12.455 c

The means with minimum common letter are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test.

Table 5
Mean comparison of rupture force and energy of cumin seed considering interaction effect of seed moisture content and seed orientation

Seed moisture content (%)	Seed orientation			
	Rupture force (N)		Rupture energy (N)	
	Vertical	Horizontal	Vertical	Horizontal
5.7	15.712 a	58.242 c	1.824 a	7.583 d
9.5	13.563 a	47.525 d	3.418 b	13.462 e
15	11.955 b	28.761 e	8.599 c	14.59 f

The means with minimum common letter are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test.

loading direction was obtained as many as 5.7-fold that of under vertical loading. In a study conducted by Singh and Goswami (1998), maximum energy absorbed for cumin seed was found to be 14.8 and 20.4 mJ at the moisture content of 7% d.b., in the horizontal and vertical orientations, respectively. Considering the interaction effect of moisture content and seed orientation, the highest difference in seed rupture energy under two various loading direction was attributable to 9.5% moisture (Fig. 5b). The effect of moisture content and orientation of loading on the rupture force and the rupture deformation of the safflower hull was studied by Baumler et al. (2006), who reported that no important difference in rupture force between both seed orientations was measured. They suggested the force required for the hull rupture decreases as the moisture content increased, and it attained a minimum value at around 11% (d.b.), followed by an increasing trend with further increase in moisture content. Paulsen (1978) for soybeans seed coat and Gupta and Das (2000) for sunflower hull reported a decrease in rupture force as moisture content increased. Teotia et al. (1989) studied the force required to cause deformation and subsequent rupture in a pumpkin seed. It was reported that the hull breaking load varied from 30 to 50 N for dry seeds and from 14 to 36 N for wet seeds, following quasi-static compression with horizontal and vertical orientations of the seed.

3.4. Loading rate

The effect of loading rate on rupture force and energy was determined for loading rate of 2 and 5 mm/min. For the horizontal loading, significant difference in force and energy was found to be at different levels of loading rate as shown in Table 6. Both rupture force and energy decreased as loading rate increased. Investigation of the interaction effect of seed orientation, seed size, and moisture content shows that under vertical loading direction, the lowest difference in rupture energy among different levels of moisture content was related to the large seeds while in other seed size categories, there was significant difference among different levels of moisture content ($P < 0.05$). These circumstances also govern on horizontal loading direction but at 5.7% moisture differences among size categories are significant. Mohsenin et al. (1963) found that the rate of deformation affected the maximum force that could be exerted by a steel plunger on apples. As the rate of deformation increased, the maximum force of rupture increased. Zoerb (1967) reported that most agricultural materials are elastic during the first portion of a load–deformation curve, but have viscoelastic properties with increased loading. Thus, once the elastic region is extended, properties are time-dependent and the effect of loading rate becomes more noticeable. It proves that the highest energy absorbed at seed rupture was as much as 15.313 mJ belonging to the small seeds at 13% moisture under horizontal loading and the lowest one was determined as 1.727 mJ associated with the large seeds at 5.7% moisture under vertical loading direction. This can attribute to high difference in rupture force values under both seed orientations, high force required to initiate small seed rupture compared to large seeds and increase in the capability of seed deformation followed by an increase in moisture content (as shown in Table 7). Based on the reports of Singh and Goswami (1998) in the case of cumin seed, the force required to initiate seed rupture decreased from 50 to 40 N and 31 to 20.3 N with an increase in moisture content from 7% to 13% d.b., for the horizontal and vertical orientations, respectively.

Both the force required to initiate seed rupture and energy absorbed at seed rupture can be strongly correlated to such variables as moisture content, seed size, and loading rate. These relationships are shown in Table 8 for vertical and horizontal seed orientations.

These relationships had a high coefficient of determination that they can be beneficial in estimating rupture force and energy for goals such as seed grinding, mechanical harvesting, handling and so on.

Table 6
Mean comparison of rupture force and energy of cumin seed considering interaction effect of loading rate and seed orientation

Loading rate (mm/min)	Seed orientation			
	Rupture force (N)		Rupture energy (N)	
	Vertical	Horizontal	Vertical	Horizontal
2	14.059 a	47.622 c	4.963 a	12.516 c
5	13.427 a	43.115 b	4.265 a	11.481 b

The means with minimum common letter are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test.

Table 7
Mean comparison of rupture force and energy of cumin seed considering interaction effect of seed size, moisture content and seed orientation

Seed size (mm)	Seed orientation					
	Vertical			Horizontal		
Seed moisture content (%)	5.7	9.5	15	5.7	9.5	15
2.1–2.5	1.965 a	3.511 b	9.16 e	5.827 c	12.34 f	15.313 h
2.6–3	1.778 a	3.563 b	8.282 ed	7.861 d	13.427 fg	14.791 gh
3.1–3.5	1.727 a	2.727 ab	8.355 ed	9.082 ed	14.617 ghi	13.665 fg

The means with minimum common letter are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test.

Table 8
Rupture force and energy as a function of seed moisture content, size, and loading rate

Seed orientation	Relationship	R^2
Vertical	$F = 11.052 - 0.731\,M + 8.509\,L + 1.405 \times 10^{-2}S^2 + 2.936 \times 10^{-2}M^2 - 1.709L^2 - 9.27 \times 10^{-2}(ML) - 5.81 \times 10^{-2}(MS) - 8.85 \times 10^{-2}(LS) + 1.859 \times 10^{-2}(MLS)$	0.98
	$E = 5.594 + 3.69 \times 10^{-3}M - 2.414L + 6.844 \times 10^{-2}S^2 + 5.617 \times 10^{-2}M^2 + 0.438L^2 - 9.59 \times 10^{-2}(ML) - 8.34 \times 10^{-2}(MS) - 8.78 \times 10^{-2}(LS) + 1.327 \times 10^{-2}(MLS)$	0.99
Horizontal	$F = 108.762 - 3.704M - 15L - 0.418S^2 - 6.36 \times 10^{-2}M^2 + 0.768L^2 + 0.563(ML) + 6.74 \times 10^{-3}(MS) + 0.411(LS) + 3.042 \times 10^{-2}(MLS)$	0.99
	$E = -21.743 + 3.816M + 4.658L - 0.874S^2 - 0.144M^2 - 0.849L^2 - 4.24 \times 10^{-2}(ML) + 0.411(MS) + 1.951(LS) - 0.142(MLS)$	0.99

E: energy; F: force; M: moisture; L: loading rate; S: seed size; R^2: determination coefficient.

4. Conclusions

- The highest energy absorbed at seed rupture was calculated as 15.313 mJ concerned with small seed at 15% moisture under horizontal loading and the lowest one, namely 1.727 mJ was attributed to large seed at 5.7% moisture under vertical seed orientations.
- Small seeds at 5.7% moisture under horizontal loading were able to withstand higher value of force as 60.049 N but large seeds at 15% moisture under vertical loading were found to be able to withstand lower value of force as 10.825 N.
- Mechanical strength and deformation capability of the cumin seed decreased and increased, respectively, as the moisture content increased according to the hypothesis that energy absorption capability of wet seeds compared to dry ones is higher, leading to higher mechanical strength to rupture during compressive loading.
- The cumin seeds are more flexible in the horizontal loading direction and the rupture under vertical loading demanding less energy than under horizontal loading. This is due to decreasing contact area of seed with loading plate and probably the occurring buckling phenomenon.
- There was a strong relationship for cumin seed energy as a function of moisture content, loading rate, and size of the seed as follows:

$$E = -8.02 + 2.24\,M + 4.34L - .1M^2 - .85L^2 - .71S^2 - .01(ML) + .38(MS) + 1.55(LS) - .13(MLS)$$

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