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ORIGINAL ARTICLE

Mechanical damage to navy beans as affected by moisture content, impact velocity and seed orientation

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Keywords
impact damage, impact velocity, moisture content, navy bean, seed orientation.

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Abstract

Introduction Mechanical damage of seeds due to harvest, handling and other process is an important factor that affects the quality of seeds. *Objectives* To evaluate the impact damage to navy bean seeds. *Methods* The study was conducted under laboratory conditions, using an impact damage assessment device. Independent variables were: seed moisture content (10, 12.5, 15, 17.5, 20, and 25% wet basis), impact velocity (5, 7.5, 10, 12.5, and 15 m/s) and seed orientation (side and end). *Results* Impact velocity, moisture content and seed orientation were all significant at the 1% level on the physical damage in seeds. Increasing the impact velocity from 5 to 15 m/s caused an increase in the mean values of damage from 0.17 to 32.88%. The mean values of physical damage decreased significantly by 1.96 times (from 27.09 to 13.79%), with increase in the moisture content from 10 to 15%. However, by a higher increase in the moisture from 15 to 25%, the mean value of damage showed a non-significant increasing trend. It was found that the relationship between beans mechanical damage with moisture content and velocity of impact was non-linear and the percentage damage to seeds was a quadratic function of moisture content and impact velocity, respectively. Impact to the end of the seeds produced the higher damage (20.61%) than side of the seeds (11.14%). *Conclusion* To minimize physical damage to navy bean seeds, the impact velocity should be limited to 10 m/s or below. The optimum level of moisture, where impact damage was minimized, was about 15%.

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Introduction

Legumes are a major food source for both humans and animals because of their nutritional benefits, such as high content in fibers and low content in fats, as well as being a cheap source of high protein content (Khazaei, 2009). Bean seed quality is greatly affected by harvesting, cleaning, drying, handling and storage activities during the seed production process. In these operations, seeds are often subjected to impact forces repeatedly against metal surfaces predisposing them to mechanical damage. The seed coat, or testa, of these seeds is very thin and is easily cracked. In addition, the plumule and radicle, parts of the seed embryo, are just under the seed coat and can easily be bruised by rough handling. The consequences of the mechanical damage are broken seeds and cracks, as well as invisible internal damages. The mechanical damage decreases the commercial and biological values of seeds. Generally, mechanical injury occurs during harvesting when the pods are threshed, but injury can also occur any time when the seeds are processed or handled including during planting (Copeland & Saettler, 1982). Harvesting legumes at low moisture make them susceptible to mechanical injury. Usually, navy beans are harvested at the moisture range from 12% to 20% (Khazaei, 2009). The mechanical resistance to the impact damage of seeds, such as beans, among other mechanical and physical properties, plays a very important role in the design of harvesting and other processing machines (Baryeh, 2002). The value of this basic information is necessary, because during operations, in these sets of equipment, seeds are subjected to impact loads, which may cause mechanical damage. Impact damage of seeds depends on a number factors, such as velocity of impact, seed structural features, seed variety, seed moisture content, stage of ripeness, fertilization level and incorrect settings of the particular working subassemblies of the machines. These parameters must be considered during harvest, transport, storage, processing and other technological stages for seeds, in which the damage occurs. Among previously stated factors, the seed moisture content and impact velocity are important factors influencing the damage (Sosnowski, 2006; Khazaei, 2009). Impact damage to seeds has been the subject of much research because of the loss in product quality incurred during harvesting, handling and processing. Researchers have used different impact damage assessment devices to conduct impact tests on seeds. A large group of devices were testing devices with rotary striker bars with controlled impact velocity and adjustable positioning of the tested seed with relation to the striker bar surface, to simulate the impact loads that seed would be subjected (Evans *et al*., 1990; Lukaszuk & Laskowski, 1995; Sosnowski, 2006). According to King and Riddols (1962), damage to beans (and to other crops) could be reduced by avoiding high cylinder speed even at low moisture content. Fiscus *et al.* (1971) tested damage to grains (corn, soybeans and wheat) because of various handling techniques and observed that dropping grains from heights greater than 13 m caused more breakage than those handled by the grain thrower or bucket elevator. Pickett (1973) indicated that threshing loss depended largely on the moisture content of bean pods. Bartsch *et al.* (1979) observed that impact damage to soybeans increased as the approach velocities increased from 10 to 15 m/s. Moisture and temperature also significantly affected impact damage. Evans *et al.* (1990) impacted soybean seeds and concluded that, seed damage increased with impact velocity and decreased with moisture content. Chawla *et al.* (1998) reported that increased drop height caused an increase in physical damage of damage to peas and beans and increased moisture level caused a decrease in the physical damage to seeds. Khazaei (2009) indicated that increasing the impact velocity from 5 to 12 m/s caused an increase in the mean percent of physical damage of kidney beans from 3.25 to 37.5%. With increasing the moisture content from 5 to 15%, the mean values of percentage of damaged beans decreased by 1.4 times.

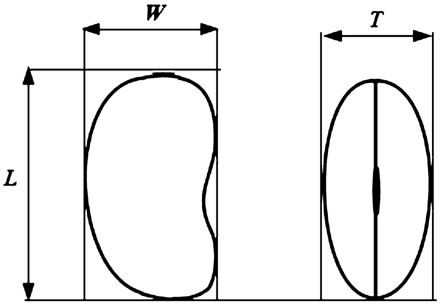

Figure 1 Typical dimensions of bean seeds: L – length, W – width, T – thickness.

Technical information and data in the scientific literature concerning the physical and physiological damages of navy beans under different impact velocity at the different moisture contents are insufficient. In light of the previously stated facts, the objective of this research was to evaluate the impact damage to navy bean seeds and determine the effects of seed moisture content, impact velocity, and seed orientation on the percentage of physical damage to beans.

Materials and Methods

Samples of navy bean (cv. *Daneshkadeh*) at optimum maturity were harvested by hand in Lorestan province, Iran, in summer, 2010, and cleaned in an air screen cleaner. The initial moisture content of seeds was 10.03% (wet basis), determined with ASAE S352.2 for edible beans (ASAE, 1988). Higher moisture content samples were prepared by adding calculated amounts of distilled water, then sealing in polyethylene bags and storing at 5 °C for 15 days. Samples were warmed to room temperature before each test and moisture content was verified. Sample mass was recorded with a digital electronic balance having an accuracy of 0.001 g. To determine the average size of the beans, 100 beans were randomly picked and their three linear dimensions namely, length (L), width (W) and thickness (T) were measured (Figure 1) using a digital micrometer, with an accuracy of 0.01 mm. The average diameter of bean was calculated by using the arithmetic mean and geometric mean of the three axial dimensions. The arithmetic mean diameter, D_a, and geometric mean diameter, D_g, of the beans were calculated by using the following relationships (Mohsenin, 1970):

$$D_a = (L + W + T)/3 \tag{1}$$

and

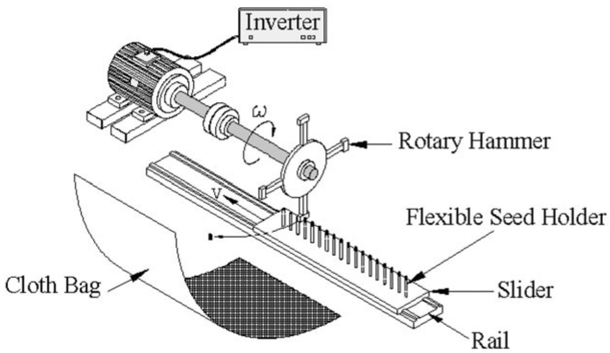

Figure 2 Diagram of the impact damage assessment device.

$$D_g = (LWT)^{1/3} \tag{2}$$

where L is the length, W is the width and T is the thickness of the bean.

The impact tests were conducted under laboratory conditions. Each sample was impacted using an impact device shown in Figure 2. Four steel impact tips (hammer), having a striking face of 5 cm wide by 20 cm high, were mounted on a disk (40 cm diameter), rotating in the vertical plane. The impact point on the steel tips moved through a path having a radius of 30 cm. A horizontal slider and rail were mounted just under the disk and impact tips. The slider has 15 seed-supporting pedestals made of flexible plastic tubing. Seeds were held on the pedestals in the desired orientation by gravity, the slider was moved toward the impact tips, and seeds were impacted one-by-one. A cloth bag behind the machine caught the impacted seeds. The impact velocity of the tips was adjusted by changing the velocity of the electromotor through an inverter set. Rigid parts of the device were covered with soft cloth to prevent additional impact to seeds. The average values of the temperature and relative humidity of the laboratory where the tests were carried out were 25 ± 2°C and 50 ± 10%, respectively.

In this study, the effects of impact velocity (5, 7.5, 10, 12.5 and 15 m/s), seed moisture content (10, 12.5, 15, 17.5, 20 and 25% wet basis) and seed orientation (side and end) were studied on the percentage physical damage in beans. The range of seeds moisture is from 10% to 25% as this includes the normal range of moisture levels during harvesting and postharvest processing for beans (Khazaei, 2009). Velocity of impact ranged from 5 to 15 m/s, included those happening in harvesters, separator, conveyors, storing system and other processing systems (Stout, 1999). Each seed was impacted on one of two orientations (Figure 3). These locations were selected to determine the specific points on the seed that are most and least resistant to impact damage. The factorial

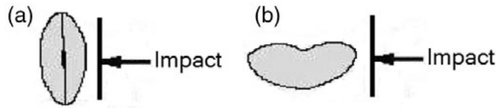

Figure 3 Seed impact orientations: (a) a side and (b) b end.

Table 1 Geometric properties of studied beans at 10.03% w.b. moisture content

Parameters	Mean	Maximum	Minimum	Standard deviation
Length (mm)	12.18	13.87	10.30	0.896
Width (mm)	7.39	8.16	6.89	0.32
Thickness (mm)	5.42	7.47	4.31	0.68
Arithmetic mean diameter (mm)	8.33	9.13	7.43	0.41
Geometric mean diameter (mm)	7.85	8.86	7.13	0.42
Weight (g)	0.33	0.43	0.20	0.04

experiment was conducted as a randomized design with three replicates. For each impact test, 100 seeds were selected randomly from each sample and impacted by using the impact device. After each impact test, seeds were inspected visually through a magnifying lens, damaged seeds include the broken, cracked, split and bruised seeds were accurately identified and weighed. The percentage of seed damage was calculated as:

$$\text{Seed damage} = \frac{(\text{weight of damaged seeds})}{[\text{weight of total seeds } (\text{damaged} + \text{undamaged})]} \times 100. \tag{3}$$

Experimental data were analyzed using analysis of variance (ANOVA) and the means were separated at the 5% probability level applying Duncan's multiple range tests in Statistical Package for the Social Sciences (SPSS) 17 software (SPSS Inc., Chicago, IL, USA). The nonlinear regression program of SAS (2001), was used to find and fit the best general models to the data and develop empirical models that explain the relationship between percentage of seed damage and the experimental variables.

Results and Discussion

Table 1 shows the mean, minimum, maximum and standard deviation of the weight, length, width, thickness, arithmetic and geometric mean diameter of the bean seeds measured at 10% w.b. moisture content. ANOVA indicated that all the three independent variables, namely, moisture content,

Table 2 Analysis of variance (mean square) for the percentage of physical damage to navy bean seeds as affected by moisture content, impact velocity and seed orientation

Source of variation	DF	Mean square	*F*-value
MC	5	1326.089	36.99**
IV	4	6612.53	184.45**
MC × IV	20	160.321	4.472**
SO	1	1034.249	112.533**
MC × SO	5	74.897	2.08ns
IV × SO	4	372.834	10.400**
MC × IV × SO	20	74.778	2.086*
Error	120	35.849	

MC, moisture content; IV, impact velocity; SO, seed orientation. **Significant at the 0.01 probability level. *Significant at the 0.05 probability level and ns, not significant.

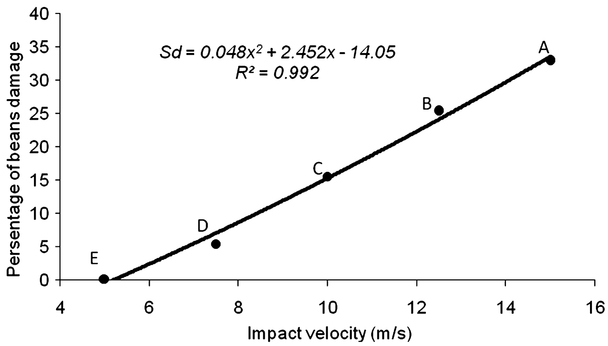

Figure 4 Effects of impact velocity on percentage damage to beans. Averages with the same letter have no significant difference at the 5% probability level.

impact velocity and seed orientation, created significant effects on the physical damage of navy bean seeds at 1% probability level ($P < 0.01$). Impact velocity had the most influence and seed moisture content the least, within the ranges studied for variables (Table 2). The interaction effects of the moisture content × impact velocity, and impact velocity × seed orientation significantly influenced the physical damage of bean seeds at 1% probability level. Meanwhile, the interaction effects of moisture content × seed orientation was not significant for the physical damage of bean seeds ($P > 0.05$). The interactions effect of the three independent variables significantly influenced the physical damage to beans at 5% probability level (Table 2).

The results of Duncan's multiple range tests for comparing the mean values of the damage to beans at different impact velocities is shown in Figure 4. It is evident that seed damage increased, as a quadratic function, with increasing impact velocity. For all the levels of impact velocity, the

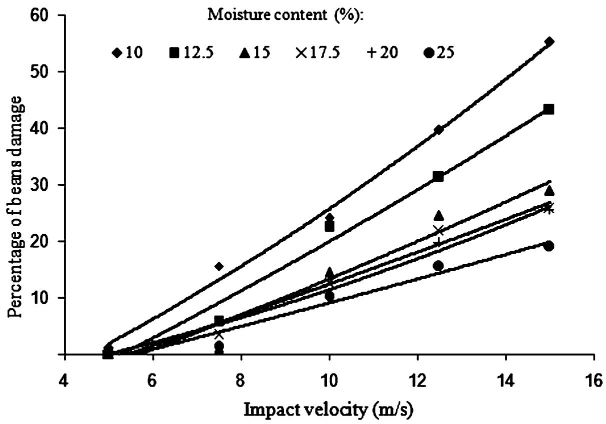

Figure 5 Navy bean damage variation with impact velocity at different seed moisture contents.

differences between the mean values of the damage are significant ($P = 0.05$). With increasing the impact velocity from 5 to 15 m/s, the mean value of the damage increased about 32.71% (from 0.17 to 32.88%). The corresponding values for increasing the impact velocity from 5 to 12.5 m/s, 5 to 10 m/s and from 5 to 7.5 m/s, were about 33.06, 22.10 and 7.85%, respectively. In addition, the corresponding values for increasing the impact velocity from 7.5 to 15, 10 to 15, and from 12.5 to 15 were about 30.48, 16/23 and 5.27%, respectively. Similar results have been reported by other researchers (Bartsch *et al.*, 1979; Liu *et al.*, 1990; Khazaei *et al.*, 2008). Sosnowski (2006) found that with an increase in impact velocity from 7 to 27 m/s, the mean value of physically damaged bean seeds of Wiejska variety increased from about 0% to 35%. Khazaei (2009) reported that increasing the impact velocity from 5 to 12 m/s caused an increase in the mean percent of physical damages of navy bean seeds from 3.25% to 37.5%.

In Figure 5, the percentage damage to seeds is plotted against the velocity of impact. The figure reveals that, at all the seed moisture contents considered, the seed damage increases as the impact velocity increases. Because of the significant interaction effect between impact velocity and moisture content, the rates of increase in damage are not the same for all levels of moisture contents. The effect of impact velocity on the damage is stronger at lower moisture contents than at higher ones. At 10% seed moisture content, percentage damage increased from 1.03% to 55.26% with increasing in the impact velocity from 5 to 15 m/s. Corresponding percentage damages were from 0% to 43.03%, 0% to 28.87%, 0% to 25.70%, 0% to 25.52%, and from 0 to 18.90% for the same velocity range, at 12.5%, 15%, 17.5%, 20% and 25% moisture contents, respectively. There were not damaged seed for the

Table 3 Equations representing the relationship between the percentage damage to seeds and impact velocity for each moisture content

Moisture content (%)	Equation	R^2
10	$S_d = 0.107V^2 + 3.1579V - 16.52$	0.9946
12.5	$S_d = 0.0502V^2 + 3.4626V - 19.81$	0.9845
15	$S_d = 0.0364V^2 + 2.51996V - 15.50$	0.9496
17.5	$S_d = 0.0171V^2 + 2.4524V - 13.81$	0.9749
20	$S_d = 0.0663V^2 + 1.2687V - 7.98$	0.9895
25	$S_d = 0.0114V^2 + 1.8505V - 10.66$	0.9601

All the indexes are significant at the level of 99.99%.
S_d = percentage physical damage to seeds; V = impact velocity (m/s).

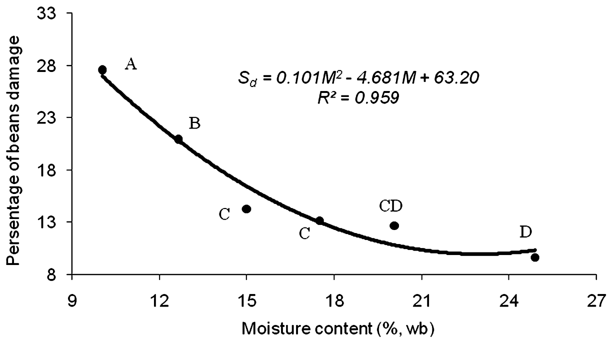

Figure 6 Effects of moisture content on percentage damage to beans. Averages with the same letter have no significant difference at the 5% probability level.

moisture content from 12.5% to 25% at employed velocity of 5 m/s. The seed damage was related to the velocity of impact in the range of 5 to 15 m/s, by regression techniques. The results showed that the percentage physical damage to seeds was a quadratic function of the velocity of impact, at all the moisture contents considered. These results are in agreement with those reported by Pickett (1973), Singh & Linvill (1977), Ptasznik *et al.* (1995) and Khazaei (2009) for other legumes. The equations representing the relationship between the percentage damage to seeds and impact velocity for each moisture content and their coefficients of determination (R^2) are presented in Table 3.

The results showed that the percentage of beans damage decreased, as a quadratic function, with increase in their moisture content (Figure 6). Many researchers have also reported similar results for the other crops (Sosnowski & Kuzniar, 1999; Parde *et al.*, 2002; Szwed & Lukaszuk, 2007; Khazaei *et al.*, 2008; Khazaei, 2009). With increasing the moisture content from 10% to 15%, the mean values of the percentage damage significantly decreased from 27.09% to 13.79% (by 1.96 times). However, by a higher increase in the

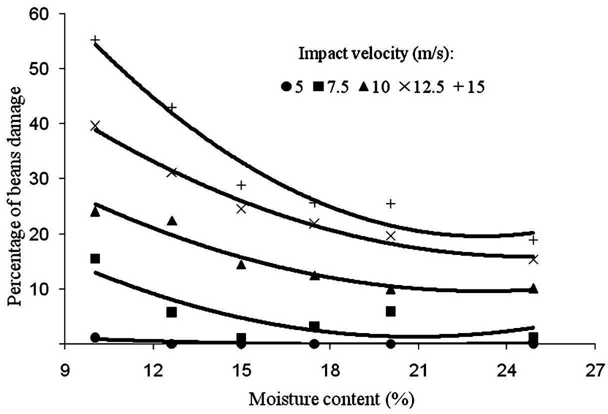

Figure 7 Beans impact damage variation with seed moisture content for different impact velocities.

moisture from 15% to 25%, the mean values of damage showed a non-significant increasing trend (Figure 6). According to numerous studies, there exists a certain optimum level of moisture content for each variety at which, under the effect of impact forces, there occurs a minimum of damage to the seeds (Szwed & Lukaszuk, 2007). Therefore, in the current study the optimum level of moisture for navy bean seeds was about 15%.

Figure 7 shows the bean seeds physical damage variation with seed moisture content for various impact velocities. As follows from Figure 7, for all the impact velocities considered, the percentage of the seed damage decreases with increase in their moisture content. These results confirm that, as the moisture content has significant effects on the elastic properties of materials of plant origin, it also has a bearing on the effects of impact damage. At higher moisture contents, the elasticity of seeds will increase, which causes that their firmness increase, thus, causes greater absorption of energy during impact and increases the resistance to damage. On the other hand, at lower moisture contents, the seeds are more brittle, thus, more prone to physical damage caused by impact (Evans *et al.*, 1990; Bergen *et al.*, 1993; Khazaei *et al.*, 2008; Khazaei, 2009).

As shown in Figure 7, the rates of increase in percent damage to seeds by decrease in their moisture content are not the same for all the levels of impact velocities. The effect of moisture content on the damage is stronger at higher impact velocities than at lower ones. At the critical range of the tests, when the moisture content decreased from 25% to 10%, the maximum rate of increase in the damage to beans was obtained for the impact velocity of 15 m/s, which was equal to 36.36% (from 18.90% to 55.26%). Corresponding values are equal to 1.03%, 14.32%, 13.98% and 24.14%, for the same

Table 4 Equations representing the relationship between the percentage damage to seeds and moisture content for each impact velocity

Impact velocity (m/s)	Equation	R^2
5	$S_d = 0.0102M^2 - 0.4054M + 3.848$	0.9752
7.5	$S_d = 0.0993M^2 - 4.140M + 44.513$	0.9632
10	$S_d = 0.0911M^2 - 4.2264M + 58.556$	0.9426
12.5	$S_d = 0.1064M^2 - 5.2648M + 81.017$	0.9871
15	$S_d = 0.2025M^2 - 9.3787M + 128.16$	0.9593

All the indexes are significant at the level of 99.99%.
S_d = percentage physical damage to seeds; M = moisture content (%).

moisture range at 5, 7.5, 10 and 12.5 m/s impact velocities, respectively. Figure 7 indicates that for all the impact velocities, relations of damage rate are nonlinear with seed moisture content. Regression analysis was used to find and fit the best general models to the data. Results showed that the percentage damage to seeds was a quadratic function of their moisture content, at all the impact velocities considered. Shardad & Herum (1977), Strona (1977), Tang *et al.* (1991), Fraczek & Slipek (1998) and Szwed & Lukaszuk (2007) observed similar behavior for other crops. The equations representing the relationship between the percentage damage to seeds and moisture content for each impact velocity and their coefficients of determination (R^2) are presented in Table 4. As follows from the relations, the effect of moisture is stronger for the higher levels of velocity than in the case of the lower ones (higher values at variable M^2).

For the optimum level of moisture content of 15% in Figure 7, the percentage damage to seeds are 0%, 1.08%, 14.46%, 24.55% and 28.87% at impact velocities of 5, 7.5, 10, 12.5 and 15 m/s, respectively, shown that at velocities lower than 10 m/s, the seed damage is lower than 10%. Based on these results, the best conditions for harvesting and other processing for navy bean seeds, in which seeds are subjected to impact loads will be at moisture contents of about 15% with impact velocities limited to 10 m/s. These features may be important in the case of selecting the time of harvesting and designing or adjusting the threshing and other mechanisms for handling or processing the seeds, to limit the impact velocity of machine parts to 10 m/s, from the viewpoint of minimizing yield losses because of the share of damaged seeds.

In Figure 8, the percentage damage to seeds is plotted against the velocity of impact at two seed orientations considered. The figure reveals that at all seed orientations, the seed damage increases as the impact velocity increases; however, because of the significant interaction effects between impact velocity and seed orientation, the rates of increase in damage are not the same for two orientations.

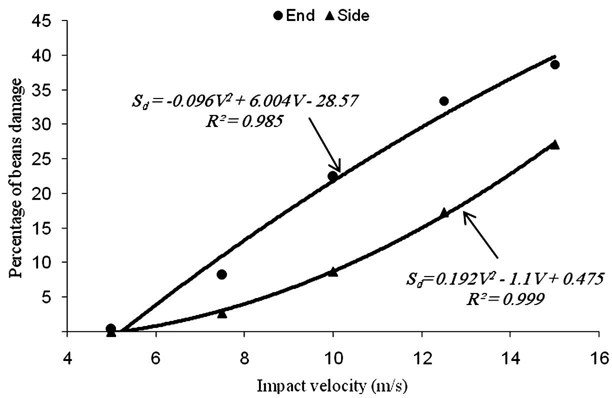

Figure 8 Beans damage variation with impact velocity at different seed orientations.

The effect of impact velocity on the damage is stronger at end orientation than at side. At end orientation, damage increased from 0.34% to 38.67% with increasing the impact velocity from 5 to 15 m/s. Corresponding values were from 0 to 27.08 at side orientation. The average percentage damage at end orientation of the seeds (20.61%) was 1.85 times higher than that of the side orientation (11.14%). Similar results have been reported by Hoki & Pickett (1973) for navy bean seeds and Evans *et al.* (1990) for soybean seeds.

Conclusions

Based on the results of this study, the following conclusions can be drawn:

(1) The data obtained from this study showed that the significant differences in the susceptibility of navy bean seeds to impact damages were revealed at different levels of seed moisture content, impact velocity and seed orientation.
(2) Impact velocity, moisture content and seed orientation significantly influenced the percentage physical damage in bean seeds, at 1% level.
(3) It was found that the percentage damage to seeds was a quadratic function of impact velocity. Increasing the impact velocity from 5 to 15 m/s caused an increase in the mean percent physical damage to seeds from 0.17 to 32.88%. To minimize physical damage to seeds, the impact velocity should be limited to 10 m/s.
(4) As the seed moisture level increased from 10% to 15%, the mean values of percentage damage to seeds decreased significantly from 27.09% to 13.79%. However, with higher increase in the moisture from 15% to 25%, the mean value of damage showed a non-significant increasing trend. There exists a certain

optimum level of moisture content at which, under the effect of impact forces, there occurs a minimum damage to the seeds. In the case of navy bean seeds, that optimum level of moisture was about 15%.

(5) The relation between navy bean seeds impact damage and its moisture content is non-linear and the percentage damage to seeds was a quadratic function of their moisture content.

(6) Impacts to the end of the seed produced the higher damage (20.61%) than side of the seed (11.14%).

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