EVALUATION AND MODELING THE MECHANICAL DAMAGE TO COWPEA SEEDS UNDER SUCCESSIVE IMPACT LOADINGS

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ABSTRACT

Mechanical damage of seeds due to harvest, handling and other process is an important factor that affects the quality and quaintly of seeds. Mechanical damage to the cowpea seeds with moisture contents of 9.65 to 25% (wet basis) at four impact velocities from 7.5 to 15 m/s, was evaluated using an impact damage assessment device. The results showed that impact velocity, moisture content, and the interaction effects of these two variables significantly influenced the percentage physical damage in cowpea seeds ($p<0.01$). Increasing the impact velocity from 7.5 to 15 m/s caused a significant ($p<0.05$) increase in the mean values of damage from 4.42 to 33.58%. The mean values of physical damage decreased significantly ($p<0.05$) by a factor of 2.77 (from 29.56 to 10.64%), with increase in the moisture content from 9.65 to 20%. However, by a higher increase in the moisture from 20 to 25%, the mean value of damage showed a non-significant increasing trend. There was an optimum moisture level of 20%, at which seed damage was minimized. An empirical model developed composed of seed moisture content and velocity of impact developed for accurately description the percentage physical damage to cowpea seeds. It was found that the model has provided satisfactory results over the whole set of values for the dependent variable.

Keywords: Mechanical damage, harvesting, handling, processing, impact, cowpea

1. INTRODUCTION

Cowpea (*Vigna unguiculata* L. Walp), an annual legume, is also commonly referred to as southern pea, blackeye pea, crowder pea, lubia, niebe, coupe or frijole. It is grown in the drier regions of the tropics covering partsof Asia and Oceania, the Middle East, southern Europe, Africa, southern USA, and Central and South America. Cowpea is used for human consumption and animal fodder and it is rich in protein.

There is a sizeable quantitative and qualitative loss of pulses, such as cowpea, during different post-harvest operations like threshing, winnowing, cleaning, drying, handling processing 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. One of the major problems experienced in mechanized harvesting, postharvest handling, and processing of pulses is mechanical damage to seeds. The consequence of the mechanical damage is broken seeds and cracks, as well as invisible internal damages. The mechanical damage decreases the commercial values of seeds. It also decreases the biological values of seeds. Hence, it is appropriate to give due emphasis to reduce qualitative as well as quantitative losses of pulses during post-harvest operations.

The mechanical resistance to the impact damage of seeds 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 (Shahbazi, 2011; Shahbazi et al. 2011a). Among above factors, the seed moisture content and impact velocity are important factors influencing the damage. Some researchers found a significant influence of the impact velocity and moisture content upon the seed damage and found that the damage increases significantly as the energy of the impact increases and as the moisture content decreases (Hoki and Picket, 1973; Bartsch et al. 1979; Paulsen et al. 1981; Evans et al. 1990). Impact damage to seeds has been the subject of much research due to 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 (Bilanski, 1966; Evans et al. 1990; Lukaszuk and Laskowski, 1995; Sosnowski, 2006; Khazaie, 2009; Shahbazi et al. 2011a and b).

During the last decade, various forms of multiple linear regression models have been widely considered to estimate the mechanical damage to seeds, based on the machine and crop parameters (Shardad and Herum, 1977; Tang et al. 1991; Sosnowski and Kuzniar, 1999; Baryeh, 2002; Szwed and Lukaszuk, 2007; Khazaie, 2009; Shahbazi et al. 2001a and b; Shahbazi, 2011).

Information relating the amount of cowpea seeds impact damage to velocity of impact and seed moisture content and modeling the damage to seeds is limited. In light of above facts, the objectives of this study were to: (1)-Evaluate the impact damage to cowpea seeds and determine the effects of impact velocity and seed moisture content on the percentage of physical damage to seeds. (2)-Develop empirical models that explain the relationship between percentage of seed physical damage and the experimental variables for cowpea seeds and evaluate the predictive performance of the models.

2. MATERIAL AND METHODS

Samples of owpea seeds at optimum maturity were harvested by hand in Lorestan province, Iran, in summer, 2011, and cleaned in an air screen cleaner. The initial moisture content was 9.54% (wet basis), determined with ASAE S352.2 for edible beans (*ASAE Standards,* 1988). Higher moisture content samples were prepared by adding calculated amounts of distilled water, then sealing in polyethylene bags, and storing at 5ºC 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.

The tests were conducted under laboratory conditions. Each sample was impacted using an impact device shown in Fig 1. The impact damage assessment device used in this study was similar to that described by Khazaie et al. (2008), Shahbazi et al. (2011a and b) and Shahbazi (2011). Four steel impact tips (hammer), having a striking face 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 with 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 by gravity and 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%±5%, respectively.

In this study, the effects of impact velocity (at 7.5, 10, 12.5 and 15 m/s) and seed moisture content (at 9.65, 12.5, 15, 17.5, 20 and 25% wet basis) were studied on percentage of physical damage in cowpea seeds. 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 7.5 to 15 m/s, including those happening in harvesters, separator, conveyors, storing system, and other processing systems (Stout and Cheze, 1999). The factorial 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 test, damaged seeds include the broken, cracked, and bruised seeds were accurately identified and sorted by visual inspection. A handheld magnifying glass was used to augment the visual inspection. The percentage of seed damage was calculated as:

$$Seed\ damage = \frac{(Weight\ of\ damaged\ seeds)}{(Weight\ of\ total\ seeds\,(damaged + undamaged))} \times 100$$

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 SPSS 17 software. The nonlinear regression program of SAS (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.

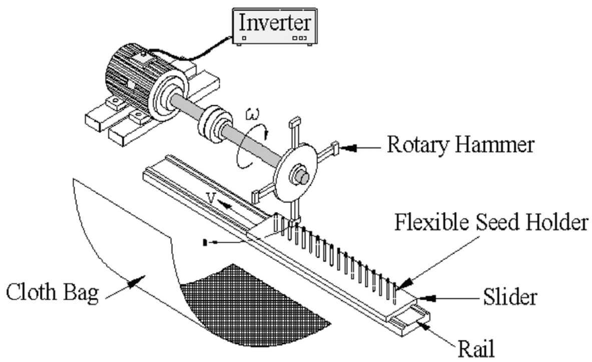

Fig.1. Diagram of the impact damage assessment device.

3. RESULTS AND DISCUSSION

Analysis of variance indicated that all the two independent variables, namely, moisture content and impact velocity, created a significant effects on the physical damage of cowpea seeds at 1% probability level (*P*<0.01). Impact velocity had a larger influence (F=904.822) than moisture content (F=239.311) within the range studied. In addition, the interaction effect of the moisture content × impact velocity significantly influenced the physical damage of bean seeds at 1% probability level (Table 1).

Table. 1. Analysis of variance (mean square error) for the percentage damage to cow pea seed as affected by moisture content and impact velocity.

Source of variation	DF	Mean Square	F value
Moisture Content (MC)	5	796.614	239.311**
Impact velocity (IM)	3	3011.959	904.822**
MC × IV	15	64.051	19.241**
Error	48	3.329	

**: significant at the 0.01 probability level.

The results of Duncan's multiple range tests for comparing the mean values of the damage to cowpea seeds at different impact velocities is shown in Fig 2. It is evident that seed damage increased, as a quadratic function, with increasing impac velocity. For all the levels of impact velocity, the differences between the mean values of the damage are significant (P=0.05). With increasing the impact velocity from 7.5 to 15 m/s, the mean value of the damage increased about 29.16% (from 4.42 to 33.58%). The corresponding values for increasing the impact velocity from 7.5 to 12.5 m/s and from 7.5 to 10 m/s were about 18.23 and 6.28%, respectively. In addition, the corresponding values for increasing the impact velocity from 10 to 15m/s and from 12.5 to 15 m/s were about 22.884 and 10.93%, respectively. Similar results about incrasing the seeds damage with impact velocity, have been reported by other researchers (Bartsch et al. 1979; Liu et al. 1990; Khazaei et al. 2008; Shahbazi, 2011; Shahbazi et al. 2011a and b). 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%. Shahbazi et al. (2011a) reported that increasing the impact velocity from 10 to 20 m/s caused an increase in the mean percent of physical damages of mung bean seeds from 0.53 to 31.78%.

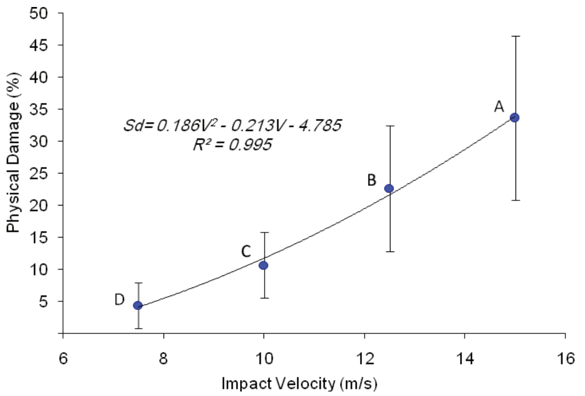

Fig. 2. Effects of impact velocity on percentage damage to cowpea seeds. Averages with the same letter have no significant difference at the 5% probability level.

In Fig 3 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. Due to 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 9.65% seed moisture content, percentage damage increased from 10.73 to 51.58% with increasing in the impact velocity from 7.5 to 15 m/s. Corresponding percentage damages were from 6.91 to 46.08%, 3.84 to 36.72%, 1.81 to 27.08, 1.08 to 21.89 and from 2.14 to 18.14% for the same velocity range, at 12.5, 15, 17.5, 20 and 25% moisture contents, respectively. The seed damage was related to the velocity of impact in the range of 7.5 to 15 m/s, by regression teqniques. 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 Picket (1973), Singh and Linvill (1977), Ptasznik et al. (1995), Khazaei (2009) and shahbazi (2011) 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 2.

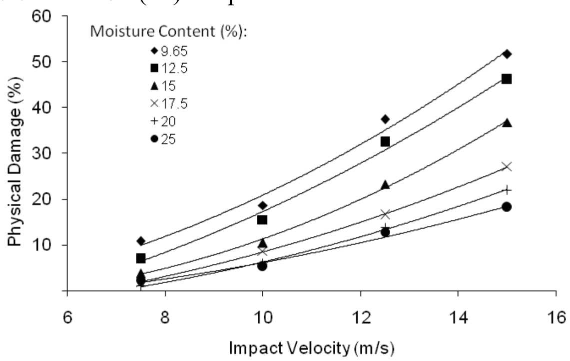

Fig. 3. Cowpea seeds damage variation with impact velocity at different seed moisture contents.

Table. 2. Equations representing the relationship between the percentage damage to seeds and impact velocity for each moisture content.

Moisture content (%)	Equation	R^2
9.65	$S_d = 0.255V^2 - 0.104V - 3.621$	0.988
12.5	$S_d = 0.203V^2 + 0793V - 11.06$	0.992
15	$S_d = 0.278V^2 - 1.801V + 1.435$	0.997
17.5	$S_d = 0.148V^2 + 0.004V - 6.481$	0.999
20	$S_d = 0.134V^2 - 0.214V - 5.052$	0.998
25	$S_d = 0.096V^2 + 0.043V - 3.931$	0.987

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

The results showed that the percentage of cowpea seeds damage decreased, as a quadratic function, with increase in their moisture content (Fig 4). Many researchers have also reported similar results for the other crops (Sosnowski and Kuzniar, 1999; Parde et al., 2002; Szwed and Lukaszuk, 2007; Khazaei et al., 2008; Khazaei, 2009). With increasing the moisture content from 9.65 to 20%, the mean values of the percentage damage significantly decreased from 29.56 to 10.64% (by a factor of 2.77). However, by a higher increase in the moisture from 20 to 25%, the mean values of damage showed a non significant increasing trend (Fig 4). 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 and Lukaszuk, 2007). Therefore, in the current study the optimum level of moisture for cowpea seeds was about 20%.

Fig 5 shows the seeds physical damage variation with seed moisture content for various impact velocities. As follows from the Fig 5, 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).

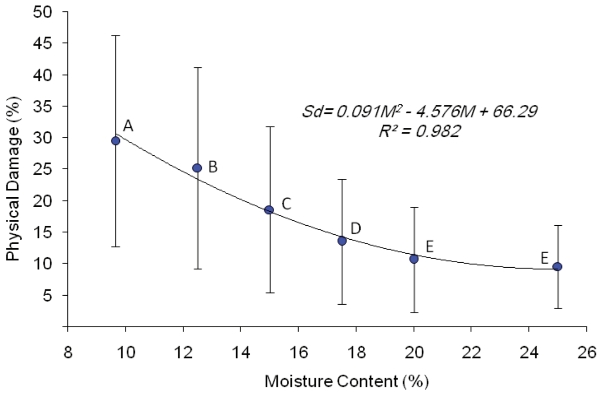

Fig. 4. Effects of moisture content on percentage damage to cowpea seeds. Averages with the same letter have no significant difference at the 5% probability level.

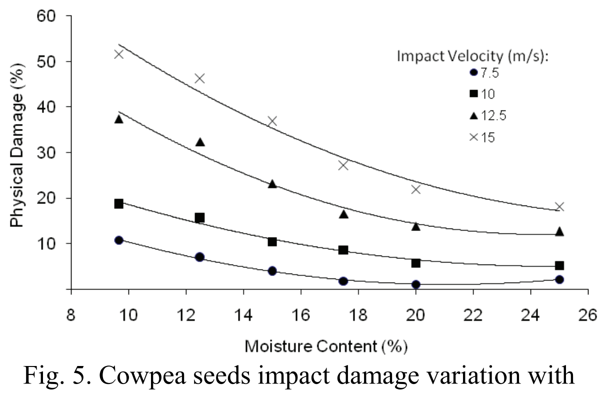

Fig. 5. Cowpea seeds impact damage variation with seed moisture content for different impact velocities.

As shown in Fig 5 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 20 to 9.65%, the maximum rate of increase in the damage to beans was obtained for the impact velocity of 15 m/s, which was equal to 29.69% (from 51.58 to 21.89%). Corresponding values are equal to 9.67, 12.78 and 23.55%, for the same moisture range at 7.5, 10 and 12.5 m/s impact velocities, respectively. Fig 5 indicates that for all the impact velocities, relations of damage rate are non-linear 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 and Herum (1977), Strona (1977), Tang et al. (1991), Fraczek and Slipek (1998) and Szwed and 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 3. 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).

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

Impact velocity (m/s)	Equation	R^2
7.5	$S_d = 0.074M^2 - 3.169M + 34.52$	0.992
10	$S_d = 0.061M^2 - 3.034M + 42.75$	0.982
12.5	$S_d = 0.124M^2 - 6.052M + 85.78$	0.974
15	$S_d = 0.106M^2 - 6.049M + 102.10$	0.995

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

For the optimum level of moisture content of 20% in Fig 5, the percentage damage to seeds are 1.08, 5.80, 13.80 and 21.89% at impact velocities of 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 cowpea seeds, in which seeds are subjected to impact loads will be at moisture contents of about 20% 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 due to the share of damaged seeds.

An empirical relationship was developed utilizing the dependence of the seeds percentage damage (S_d, %) on parameters such as seed moisture content (M, %), impact velocity (V, m/s), and $M \times V$ as independent variables, with the help of regression techniques. The relationship is given as follows:

$$S_d = -2.757 - 1.781M + 3.913V - 0.248MV + 0.092M^2 + 0.186V^2 \quad R^2 = 0.975$$

(The regression statistics for the model indicated that all terms were significant effects (at the 99.5% level) on the accuracy of the model. The p-value of predicting equation was <0.0001. The performance of the selected relationship for the prediction percentage of damage to cowpea seeds due to impact is shown in Fig 6. This figure shows the predicted percentage of damage data versus the same set of measured data. The scatter plot showed no tendency for the model to under- or over-estimate the predicted percentage of damage data. It is observed that the predictive capability was good and data points were well compressed about the ideal of unity-slope line selected. The linear adjustment between the observed and estimated values gives a slope practically equal to 1 (Y=0.971X +0.720). The resulting correlation coefficient and the p-value were 0.974 and <0.0001, respectively, for the regression between observed and estimated values (Fig 6), indicating that the model provided satisfactory results over the whole set of values for the dependent variable.

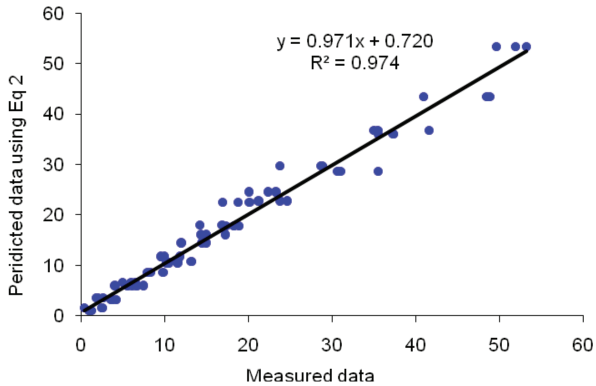

Fig. 6. Correlation between the actual and the predicted data by the mathematical model (Eq. 2).

4. CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn: The data obtained from this study showed that the significant differences in the susceptibility of cowpea seeds to impact damages were revealed at different levels of seed moisture content and impact velocity. Impact velocity, moisture content, and the interaction effects of these two variables significantly influenced the percentage physical damage in cowpea seeds (p<0.01). It was found that the percentage damage to seeds was a quadratic function of impact velocity. Increasing the impact velocity from 7.5 to 15 m/s caused an increase in the mean percent physical damage to seeds from 4.42 to 33.58%. To minimize physical damage to seeds, the impact velocity should be limited to 10 m/s. As moisture content increased from 9.65 to 20% the mean values of damage to seeds decreased by a factor of 2.77 following a quadratic relationship. The optimum level of moisture, where impact damage was minimized, was about 20%. The mechanical damage to cowpea seeds under impact loading was accurately described by an empirical model composed of moisture content and impact velocity.

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