Segregation of canola, kidney bean and soybean in wheat during bin loading

by

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Abstract

Segregation is an important phenomenon in bulk grain handling and the distribution of Fines, Foreign materials and Dockage (FFD) in stored grain has been studied in the literature. In the reported studies, FFD was characterized only by its size which has resulted in an inability to make meaningful comparisons as FFD of the same size may have different physical properties.

In this study, kidney bean, soybean and canola were used to represent FFD in bulk wheat and these grains were referred to as “other grains”. A test bin of 2 m diameter was loaded with wheat grain with 0, 3 and 6% other grains. Trials were conducted at three drop heights of 80, 160 and 240 cm. After the bin was loaded, samples were collected at the following six locations along a radius: 0, 18.8, 37.6, 56.4, 75.2 and 94 cm from the centre. The bulk density was measure for each sample and the samples were then sieved to determine the amount of other at each location. Also, the orientation of grains was studied by pouring melted wax at three locations along another radius.

The orientation of the major axes of wheat, kidney bean and soybean was along the radius of the bin. The canola seeds were found more at the periphery of the bin and this could be due to impact segregation. The kidney beans and soybeans were found more near the mid locations and centre of the bin. The effects of avalanches, rolling, sliding and embedding were observed. The percentage of other grains inside the grain mixture before loading into the test bin did not have a significant effect on the distribution of other grains after loading. The drop height significantly affected the amount of canola at different locations inside the test bin.

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1 Introduction

Grains need to be stored in a manner to maintain their quality throughout the storage period. In commercial storage, bulk grains handled contains materials other than clean grain. Apart from the desired grains there is also dockage which is defined by the Canadian Grain Commission (CGC) (2016a) as “any material intermixed with a parcel of grain, other than kernels of grain of a standard of quality fixed by or under this Act for a grade of that grain, that must and can be separated from the parcel of grain before that grade can be assigned to the grain”.

In the literature, different terminologies such as “foreign material”, “fines”, “broken grain” and “chaff” have been used to denote other materials in the grain bulk like broken kernels, plant materials, other seeds, insect fragments, soil particles and fine particles. In order to avoid confusion, some of these terms are defined below based on the standards of the Canadian Grain Commission. Foreign material is defined as “material other than grain of the same class that remains in the sample after the removal of dockage” (Canadian Grain Commission, 2016b). Chaff and fine materials are not defined by CGC but based on CGC, chaff is considered as “roughage” which is defined as “a type of foreign material that includes chaff, loose hulls, empty seed pods, knuckles, etc. that are readily removable by aspiration, handpicking, or other cleaning procedures”. Fine materials are materials that are smaller than the desired grain and are separated by sieving or aspiration (Stroshine, 1992). In this study, the materials other than the desired grain will be referred together as fines, foreign materials and dockage (FFD).

The materials constituting the FFD usually differ from the grains in their physical properties and so they tend to segregate from the remaining bulk. Their distribution in the bulk grain is not uniform i.e. it differs at different locations (Chang et al., 1986; Jayas et al., 1987). Segregation occurs when the grain bulk is subjected to any movement or disturbance. Grain has to be handled at different stages from harvest to final consumption and thus segregation cannot be avoided.

Temperature and moisture content are the two most important factors affecting the quality of stored grain, and it is important to maintain the grain at safe storage temperatures and moisture contents. This purpose is served by aeration or drying of grain bulk. During aeration or drying, the grain and FFD exerts a resistance to airflow and the resistance exerted by clean grain is different from the grain with FFD (Haque et al., 1978; Kumar and Muir, 1986; Jayas and Sokhansanj, 1989). As the distribution of FFD is not uniform throughout the grain bulk, the resistance offered to airflow is not uniform. This affects the uniformity of airflow and this in turn affects the uniformity of temperature and moisture content. A location with high moisture content and temperature might result in grain deterioration.

Fine particles tend to collect more in the centre of the bin (Chang et al., 1983; Chang et al., 1986), and when unloaded, the first few batches will have more fine particles than the average fine content of the grain in the bin. This could affect the grade assigned to the grain lot and in turn affects the monetary value. The presence of fine dust also has other negative effects like affecting the workers' health and potentially causing explosions in grain bins.

The presence of FFD has been shown to increase the emergence and multiplication of some species of stored-product insects in wheat (McGregor, 1964; Sinha, 1975). As grain dust produced by insects alters the bulk density of grain (Reed and Milliken, 1988), the physical properties of the infested regions might change, and this will affect the monetary value of the grain. In addition to this, the effect of fumigants used in grain storage to eliminate insects was also have reduced effectiveness by FFD (Harein, 1961). The moisture content and fungal infestation were higher in the FFD in wheat and rapeseed than in the stored whole kernels (Prasad, 1974; Prasad et al., 1978).

As the FFD has a wide range of effects on grain storage, it is important to understand its distribution and the mechanisms behind it.

1.1 Objective

The objective of this study was to investigate the effect of drop height and percentage of other grains (red kidney bean, soybean, and canola) on the distribution of these grains in wheat and bulk density of the mixture.

2 Literature review

2.1 *Effects of dockage distribution*

2.1.1 Bulk density and porosity

Dockage usually has different physical properties than the grain itself, and so it alters the bulk density and porosity of bulk grain when it is mixed with the grain. The effect of chaff and fines on bulk density and porosity of canola was studied for 0 to 25% by weight of chaff and fines. There was a linear decrease in bulk density and increase in porosity with the increase in amount of either chaff or fines, and the effect of chaff is more significant than the effect of fines. An empirical linear relationship was developed to predict the values of bulk density and porosity from the amount of chaff and fines by percent weight (Eq. 1) (Jayas et al., 1989).

$$P = X_0 + X_1 * C + X_2 * F \tag{1}$$

where, P = physical property of canola, either bulk density or porosity

X_0, X_1, X_2 = constants dependent on method of fill and the desired physical property of canola

C = chaff content of the sample in percent, by weight

F = fines content of the sample in percent, by weight

2.1.2 Airflow resistance

Shedd (1953) determined airflow resistance for selected grains under different packing conditions, moisture contents and amounts of foreign material and provided a chart for pressure drop per unit depth of grain at different airflow rates for loose-filled clean dry grains. He found that the curves of any one grain under any conditions of foreign material content and moisture content are different from that of the clean grain. The airflow resistance increased with foreign materials finer than the grains and decreased with coarser foreign materials. The relationship between airflow rate and airflow resistance was expressed as follows.

$$Q = A\left(\frac{\Delta P}{L}\right)^{B} \qquad (2)$$

where, Q = airflow rate, $m^3/s.m^2$

ΔP = pressure drop, Pa

L = length of the column, m

A and B = empirical constants

For the same airflow rate, the airflow resistance of maize, increased with increased amount of fines (Haque et al., 1978; Chang et al., 1981; ASAE, 2016) and decreased with the increase of fine size (Grama et al., 1984; Yang et al., 1990). The experimental data for airflow resistance of maize and canola with fines were fitted by Haque et al. (1978) and Jayas et al. (1989) to the Hukill and Ives equation with an additional term for amount of fine materials (Eq. 3) which was adopted by the ASAE (2016).

$$\left(\frac{\Delta P}{L}\right)_{corrected} = \left(\frac{\Delta P}{L}\right)_{clean} \left(1 + k(fm)\right) \tag{3}$$

where, L = depth of grain bed, m

k = a correction factor for effect of fines

fm = percentage of fine materials, decimal

The relationship between airflow resistance and airflow rate for maize, wheat and grain sorghum was expressed using a general equation (Eq. 4) (Chang et al., 1981; Chang et al., 1983).

$$Q = EXP[A + B \cdot lnP + C(lnP)^2] \tag{4}$$

where, P = airflow resistance, Pa/m

B and C = common coefficients

A = coefficient based on bulk density and fine material content

The airflow resistance offered by wheat with dockage was higher than clean wheat (Kumar and Muir, 1986). A similar conclusion was drawn about the airflow resistance offered by oats with foreign material (Pagano et al., 2010). The non-linear regression model by Haque et al. (1978) (Eq. 5) was used to fit the experimental data for oats (Pagano et al., 2010).

$$\Delta P = C_1 Q + C_2 Q^2 + C_3 Q(fm) \tag{5}$$

where, C_1, C_2 and C_3 = constants

The resistance to airflow offered by different percentages of seven grades of fines (graded based on size) mixed with whole maize kernels was studied and two least squares linear regression models were developed to predict Clean Corn Multiplier (CCM) from percentage of fines in maize (Grama et al., 1984). Clean Corn Multiplier was defined as the ratio of the pressure drop of maize with fines to the pressure drop of clean maize at the same airflow rate. The least squares model developed for fines (retained between sieves with openings of 6.4 and 5.6 mm) was as follows.

$$CCM = 0.030X + 1.0 \tag{6}$$

where, CCM = Clean Corn Multiplier

X = percentage of fines

The airflow resistance of fines removed from maize by screening and aspiration was studied (Yang et al., 1990). The aspirated materials removed by lower airflow rates had offered higher resistance. Modified Ergun's equation (Eq. 7) was used to fit the experimental data.

$$\Delta P = A\frac{(1-E)^2V}{E^3} + B\frac{(1-E)V^2}{E^3} \tag{7}$$

where, A and B = Constants

E = fraction of voids

V = apparent fluid velocity

$$E = 1 - \frac{BD}{PD} \tag{8}$$

where, BD = bulk density

PD = particle density

2.2 Mechanisms of segregation

Several mechanisms of segregation were proposed in bulk material handling (Mosby et al., 1996; de Silva et al., 2000) and a few of them are outlined below.

2.2.1 Sieving

When a mixture of coarse and fine particles falls over the centre of a pile, the coarse particles slide over the inclined surface. If the fine particles are small enough to pass through the interparticle space among the coarse particles, then they will come down through the voids in the sliding layers of coarse particles (Chang et al., 1981; Chang et al., 1983; Chang et al., 1986). This segregation occurs until the coarse particles stop moving or until there are no more fine particles to come down. Sieving is exhibited when fine content is low and there are enough coarse particles to sieve through.

2.2.2 Trajectory effects

If a mixture of particles with different physical properties is discharged from an inclined chute or spreader, larger particles have higher momentum and travel farther from the point of discharge but the smaller particles fall nearby due to air drag. This effect is not significant if the discharge outlet is vertically pointed down (Chang et al., 1983).

2.2.3 Rolling

When a bulk material is filled in a bin, it forms a pile. After a considerable pile is formed, the coarse particles that fall over the pile will roll over the inclined surface and reach the edge of the pile. The fine particles have more resistance to rolling and thus get retained before reaching the edge (Parker et al., 2005). This effect is significant if the particles' sphericity is close to 1 and rate of filling is low.

2.2.4 Impact segregation and push-away effects

Impact segregation occurs due to collision among particles during grain loading. When impacted, particles with smaller momentum will be bounced off from the centre of the pile and located away (Parker et al., 2005). Push-away effects occur when a particle of higher density falls on particles of lower density; the former tends to push away the latter and occupies its place. This will result in higher concentration of less dense particles in the periphery and denser particles near the centre.

2.2.5 Embedding

It is the process where heavier particles when hitting the apex of the pile, break the surface and get embedded into it (Parker et al., 2005).

2.2.6 Air current effects and fluidization effects

When a material containing a considerable amount of fine particles is loaded into a container through a central opening, the falling stream of material induces an air current inside the container that carries the fine particles to the periphery of the container. Air current effects increase with the increase of drop height, and result in a higher concentration of coarse particles near the centre. Fluidization effects occur when a grain bin is loaded and the grains fall down to the bottom of the bin, but fine particles may get aerated. The fine particles may settle on the surface of the grain pile after loading is completed.

2.3 Factors affecting FFD distribution

2.3.1 Filling method

Grains can get damaged as they go through various stages during harvest, storage and post-harvest operations (Waelti and Buchele, 1969; Fiscus et al., 1971; Hall, 1974; Martin and Stephens, 1977) causing fines to be generated. The amount of fine materials differs with the method of filling (with and without spreaders) and the number of times the grain is handled. The fine materials in maize inside a bin were more concentrated in the region directly below the filling point when loaded with a central spout, whereas the distribution of fines was more uniform (less coefficient of variability) when loaded with spreaders (Stephens and Foster, 1976; Chang et al., 1981). But the uniformity of fine material distribution in wheat was not improved by the use of spreader and in case of grain sorghum the uniformity was higher without spreaders (Stephens and Foster, 1978). A small improvement in uniformity was reported for fines in canola when bins were filled using a conical spreader rather than using a central spout as the spreader increased the amount of chaff and fines at the center and reduced it near the wall. Quadratic equations (Eqs. 9, 10, 11 & 12) were developed to mathematically represent the distribution of fines and chaff in canola bins (Jayas et al., 1987). For chaff distribution in a central spout fill,

$$\frac{C_s}{\bar{C}_s} = 0.722 - 0.740\, r + 0.535\, r^2 \tag{9}$$

where, C_s = chaff at radius r for spout-filled bin

$\bar{C}_s$ = mean chaff content for spout-filled bin

r = location along bin radius measured from central axis, m

For distribution of fines in a central spout fill,

$$\frac{F_s}{\bar{F}_s} = 1.093 - 0.474\, r + 0.241\, r^2 \qquad (10)$$

where, F_s = fines at radius r for spout-filled bins

$\bar{F}_s$ = mean fines for spout-filled bins

For distribution of chaff in a spreader fill,

$$\frac{C_c}{\bar{C}_c} = 0.960 - 0.866\, r + 0.520\, r^2 \qquad (11)$$

where, C_c = chaff at radius r for spreader-filled bin

$\bar{C}_c$ = mean chaff content for spreader-filled bin

For distribution of fines in a spreader fill,

$$\frac{F_c}{\bar{F}_c} = 1.269 - 0.466\, r + 0.166\, r^2 \qquad (12)$$

where, F_c = fines at radius r for spreader-filled bins

$\bar{F}_c$ = mean fines for spreader-filled bins

2.3.2 Rate of filling

Some studies have been done on the effect of rate of filling the grain bin on the distribution of fines. The velocity of grain entering the bin was reduced by adding an orifice at the end of the spout and decreasing the diameter of its opening and such a flow has been referred to as "choke-flow". The velocity of grain in a spout-flow has been shown to be higher than that with the choke-flow method (less than 1 m/s) (Chang et al., 1986). There was no significant difference in the distribution of fines in maize, wheat and grain sorghum when filled with and without spreader if loading is done by the choke-flow method (Chang et al., 1983). A comparison between choke-flow and spout-flow fill was done in maize and an improvement in fines distribution was observed in the choke-flow method (Chang et al., 1986).

2.3.3 Drop height

Few studies were conducted on the effect of drop height on FFD distribution (Chang et al., 1986; Parker et al., 2005). Drop height had no significant effect on fines distribution in maize when filled using choke-flow and spout-flow methods (Chang et al., 1986). An increase in drop height increased the amount of both larger and smaller spherical dockage in wheat at the centre and near the wall in a square bin (Parker et al., 2005). Drop height seemed to have a little effect on horizontal distribution of chaff and fines in canola filled using a central spout and had no significant effect when filled with a spreader (Jayas et al., 1987).

2.3.4 Grain type

The distribution of FFD should be affected by the grain type as different grains have varied physical properties and the type of FFD present in them. The segregation of fine materials in maize was higher than in wheat and grain sorghum in a study (Stephens & Foster, 1978). But in another study when the distribution of fine materials was compared between wheat, sorghum and maize, the trend was the same for all the grains (Chang et al., 1983) with the fine materials being higher at the centre and lower near the periphery. This general trend was not observed in the fines distributed in canola (Jayas et al., 1987).

2.3.5 Moisture content

Moisture content (m.c.) affects the flow properties of wheat (Bian, 2014). The fine materials (particles that passed through a 4.8 mm round-hole sieve) in maize had higher concentration in the centre of the bin at 13% m.c. than at 12% and there was an opposite trend at the locations near the periphery (Chang et al., 1981). Similarly, segregation in sand particles has been shown to be reduced by increase in moisture content (Bagster, 1996). The distribution of dockage smaller than wheat in a bin of the same size (4.2 m) was different at two different moisture contents of 10.4 and 13.2% (Prasad, 1974). At 13.2% m.c. the amount of dockage was highest at the periphery of the bin, whereas at 10.4% m.c. the peak level was at around 45 cm from the periphery towards the centre.

2.3.6 Bin size

As the diameter of the storage bin increases, the width of the pile formed will be increased. This will allow the grain at the surface to travel a longer distance and this might increase the chances of segregation. The effect of bin size on the distribution of dockage was shown in a study with wheat bins (Prasad, 1974). The trend of the distribution of dockage smaller than wheat was the same in two bins of 4.2 m and 5.4 m diameter and the peak levels of dockage was 45 cm from the periphery in both of the bins.

2.3.7 Size of FFD

The fines (size < 4.8 mm) in maize were more concentrated near the bin centre than at the periphery (Chang et al., 1986). The amount of grains smaller than wheat (canola) was significantly higher in the centre than near the periphery (Parker et al., 2005; Parker, 2005). But a contradicting result was observed in the distribution of fines (<1.18 mm) in canola

(Jayas et al., 1987) where the amount of fines at the centre was similar to that of the periphery. This is supported by the change in the distribution of coarse particles based on the size of fine particles in sand (Bagster, 1996). In another study, the amount of dockage smaller than wheat was maximum at the mid radial distance (Prasad, 1974; Prasad, Muir, & Wallace, 1978).

Few studies have been done on distribution of FFD larger than the grain. The amount of spherical grains larger than wheat accumulated more near the walls and the corner in a square bin (Parker et al., 2005). The amount of chaff in canola bins was higher near the wall and lowest at a distance of 0.6 to 0.8 m from the centre of the bin when filled using a central spout (Jayas et al., 1987). A similar result was observed where the amount of dockage larger than rapeseed was significantly higher near the bin wall (Prasad, 1974; Prasad et al., 1978).

Size segregation in materials other than grains has been studied and it was shown that contradicting trends can occur based on the type of material handled. When coal was centrally loaded in a silo, it resulted in more of coarse particles at the periphery and fine particles around the centre (Stock, 1944). But fine particles of alumina (<0.05 mm) tends to get settled in the periphery of the container due to the air currents leading to higher concentration of coarse particles near the centre (De Silva and Enstad, 1991).

2.3.8 Other factors

In general, particles of smaller size, less spherical shape and higher density tend to collect in the centre of the bin and the pattern of segregation depends on various factors like mixing ratio, feed rate, and the size of the pile formed (Kunio et al., 1972; Shinohara, 1979; Shinohara and Miyata, 1984). An increase in the chaff content has been shown to reduce the flowability of a wheat bulk (Bian, 2014). The effect of other factors like percentage of FFD, shape and density could not be studied in detail from previous studies because, to compare the effect of any one of these factors, other factors have to be kept consistent which was not the condition in previous studies.

Based on previous research, the following gaps have been identified.

- When distribution of FFD is studied in different grain types in the literature, the physical properties of the grain itself, the type and physical properties of FFD have varied considerably. For example, wheat and canola grains have different physical properties and so do the FFD found in them. Because of this, it is hard to make direct comparisons about the FFD distribution in both grains.
- In most studies, the FFD is defined only by size and not by other physical properties. This makes it harder to make a unanimous conclusion about the distribution, as FFD of same size may have a wide range of other physical properties such as shape and density which have been shown to impact segregation and distribution of bulk solids (Brown, 1939).

In order to overcome the above issues and to have a unified conclusion irrespective of the properties of FFD, studies have to be done with the FFD and the grain being described by definite physical properties like size, shape, and density, and the effect of different factors on these physical properties must be studied. This will also be useful to create general mathematical models to describe segregation and distribution of FFD. Therefore, in this study, we used grains with different size, shape, and density to represent FFD with a wide range of physical properties.

3 Materials and methods

3.1 Grain preparation

Wheat (AAC Elie variety) was used as the main tested grain, and canola (*Brassica napus*) (Bulk commercial canola from Agri-Tel Grain Ltd., Beausejour, MB, Canada), soybean (*Glycine max*) (S007-Y4 variety) and kidney bean (*Phaseolus vulgaris*) (Light red kidney bean from AGT Foods, Regina, SK, Canada) were used to represent FFD (Fig. 1).

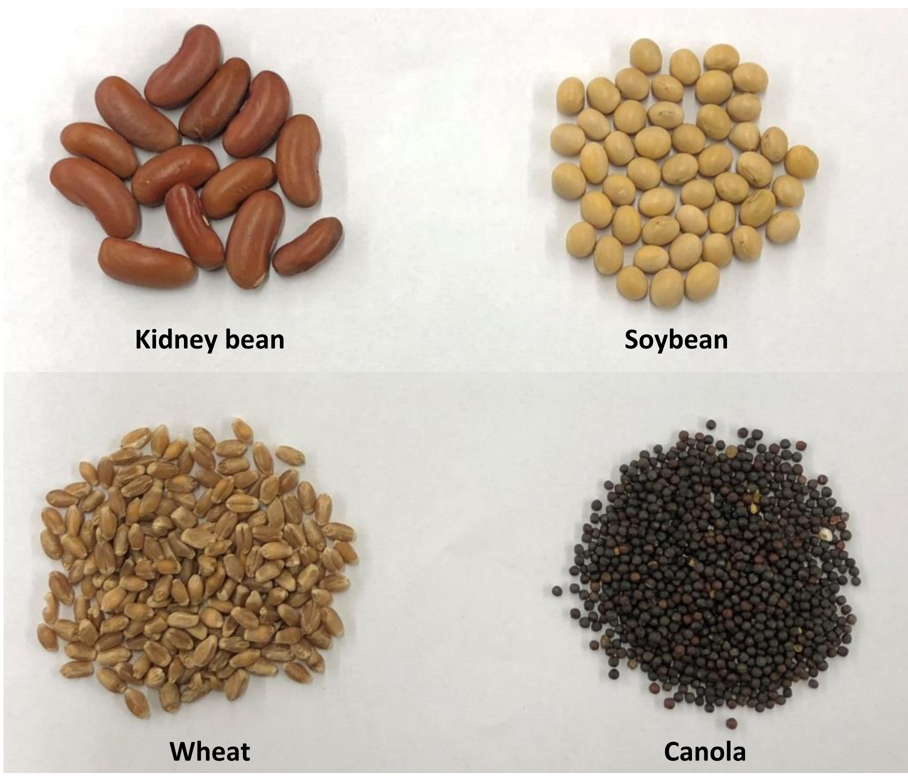

Fig. 1 Grains used in the study.

In this thesis, canola, soybean and kidney bean were referred to as other grains. The reasons for choosing these grains were: 1) the shape and size of the grains are relatively stable; 2) it is easy to separate these mixed grains after loading and unloading; 3) different shapes and size of the grains can be studied in one test, so the information from one study is maximized; 4) it is easy to identify and separate the broken grain during the data collection; and 5) these grains are occasionally present as foreign materials in wheat in the Canadian grain handling system.

About one tonne of wheat was used for each trial; therefore, it was not feasible to use a fresh batch of mixture of grains for each trial. After each trial, a three dimensional vibratory separator (SWECO, Model XS40, Florence, Kentucky) was used to separate the mixture of the grains. Three sieves with apertures of 7.09, 4.75 and 2.45 mm (from top to bottom) were used. The separator was operated with the top weights at “9” position and the bottom weights to provide 35º lead angle. The separated grains were then used again for the next replicate or treatment. At the beginning of the experiment, all the grains were fed into the separator and only specific size ranges (Table 1) were used for the trials. The physical properties of the grains were measured at the end of the experiment (Table 1). The length, width and thickness were measured by using a caliper with 0.05 mm resolution for all grains except canola where only length and width were measured because of the smaller size of the canola seeds.

Table 1 Size range and physical properties of the grains (mean ± SD) used in the study.

Grain	Range (mm) [a]	Bulk density (kg/m^3)	1000-kernel Weight (g)	1000-kernel volume (mL)	Physical dimensions (mm) [b]		
					Length	Width	Thickness
Kidney bean	>4.75	715.3±7.3	515.6±0.3	433.3±5.8	17.2±1.0	8.3±0.5	5.9±0.5
Soybean	>4.75	748.0±0.8	124.0±1.3	102.7±1.2	6.7±0.4	5.9±0.3	5.1±0.3
Wheat	4.75>x>2.45	807.7±0.9	33.4±0.4	26.7±0.6	5.7±0.4	3.2±0.2	2.8±0.2
Canola	2.00>x>1.41	624.5±0.4	3.1±0.1	3.1±0.2	1.8±0.1	1.7±0.1	-

[a] For example, wheat kernels that passed through the sieve with 4.75 mm opening and retained over the sieve with 2.45 mm opening was used for the experiment.

[b] Mean values of 50 kernels.

The moisture contents of wheat, kidney bean, soybean and canola at the time of the measurement of the physical properties were 7.31±0.06, 9.92±0.06, 4.84±0.02 and 4.33±0.03%; respectively.

Before the experiment, wheat, canola, soybean and kidney bean were held at room conditions (14.7±2.2℃ and 12.9±1.6% RH) for 24 days and left to equilibrate with the room's relative humidity. During this time wheat was stored in grain bags of around 60 cm height and other grains were stored in grain bags of 25 cm height and grains were not turned. During the experiment, the grain was constantly turned when it was conveyed through the auger, loaded and unloaded from the test bin. The experiments were conducted inside the Canadian Wheat Board Centre for Grain Storage Research over a period of 40 days. The moisture content was measured at the beginning and the end of the experiment. The test weight of the grain was measured before the trials (ASABE, 2012; 2016a).

The trials were conducted at 0, 3 and 6% of other grains by weight in 1 tonne of wheat bulk. At 3 and 6% other grain levels, each of the other grains accounted for 1 and 2% of wheat grain, respectively. For example, to make the 3% of other grain level, 10 kg of canola, 10 kg of soybean, 10 kg of kidney bean, and 970 kg of wheat were used for a replicate. Each treatment was replicated thrice.

3.2 Holding bins and test bin

To mix wheat with the other grains at the required percentages, three bins were used to hold the grain separately before the grains were mixed and loaded into the test bin (Fig. 2). The bin used to hold the wheat was a 1.25 m^3 hopper bottom PVC bin (Fig. 2) and it was loaded using auger no. 1 (4.8 m length and 10 cm diameter). Another hopper bottom PVC bin with 0.77 m diameter and 1 m height was mounted on a steel frame to hold canola. A square bin (1.15 m height and 0.38 m width) was used to hold soybean and kidney bean. The outlets from the bins discharging canola, soybean and kidney bean were connected to PVC pipes (7 cm diameter) and directed to the feed hopper of the auger no. 2 (4.75 m length and 9.9 cm diameter). The test bin was a circular steel ring of 20 cm height fabricated by welding sheet metal.

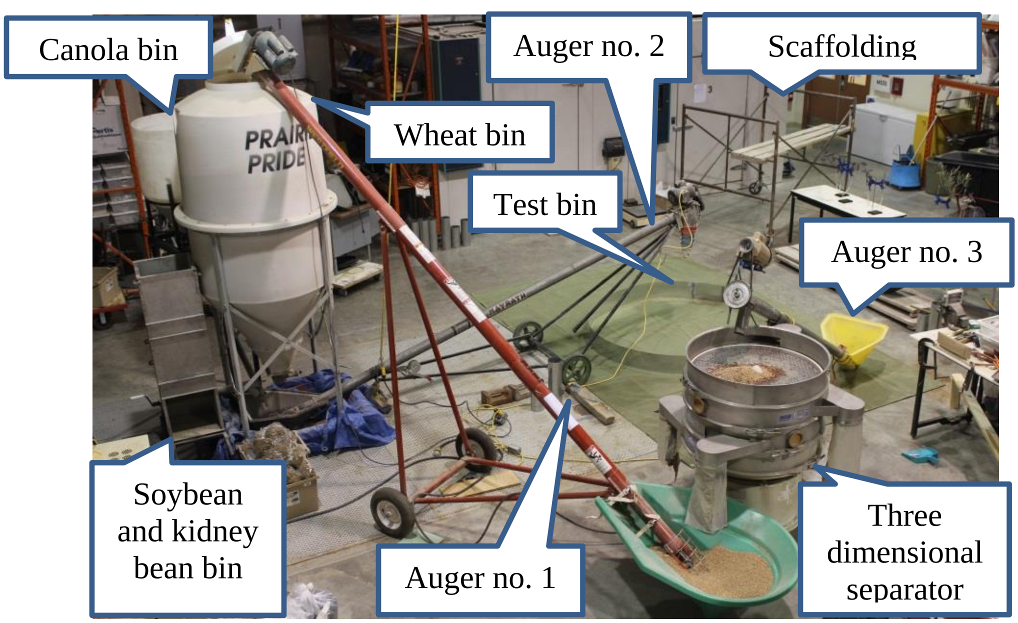

Fig. 2 Experimental setup.

3.3 Grain flow rate control

The flow rates of the grains discharged from each bin had to be calibrated to achieve the required percentages of other grains in wheat. The flow rates of wheat and canola were controlled by the double slide gates at the bottom of the hopper bottom bins. The top slide gate was kept at a fixed position based on required flow rate and the bottom slide gate was changed to regulate wheat and canola discharge. The flow rates of soybean and kidney bean were controlled by the number of rotations of the screw conveyor. The flow rate of wheat used in the experiment was 57 kg/min for trials with 0 and 3% other grains and 46 kg/min for the trials with 6% other grains. The flow rate of each of the other grains was calculated based on the flow rate of wheat and it was 0.58 and 0.92 kg/min for trials with 3 and 6% other grains, respectively. The position of the slide gate in the canola bin was set accordingly to achieve the desired flow rate. The slide gate was moved 1.6 and 2 cm from the fully closed position for 3% and 6% other grains, respectively. The number of rotations of the screw auger to discharge soybean and kidney bean were 17 and 26 rpm for 3 and 6% of other grains, respectively.

3.4 Loading and videotaping

The auger no. 2 was used to mix all the grains and load the mixture to the test bin. The test bin was placed over a tarpaulin (1.125 mm thick) to reduce any bouncing of grain during loading (Parker et al., 2005), and centered directly under the spout of the auger no. 2. During the test, the auger no. 2 was turned on first, the bottom slide gates of the wheat and canola bin were opened fully, and the screw conveyor was rotated to discharge soybean and kidney bean at the same time.

The pile formation was videotaped and still images and other observations were made using three cameras: 1) GoPro Hero 5 Black (San Mateo, US), 2) iPhone 8 (Cupertino, US), 3) Canon 600D (T3i, Tokyo, Japan). The videos and images were later analysed to observe the behaviour of different grains while loading. The test bin was loaded until the grain overflowed.

3.5 Sampling and unloading

The total height of the grain pile was about 60 cm with a conical portion of 40 cm height. After loading, the top 30 cm of the cone was removed by shovelling, and care was taken to reduce the disturbance in the remaining grain bulk. Wax was melted in a beaker over a hot plate heater and around 250 mL of melted wax (at about 110ºC) was poured at each of three locations (18.8, 56.4 and 96 cm from the centre) in the test bin (Fig. 3). The melted wax reached 10 to 15 cm below the grain surface. To aid sampling at different locations, a scaffolding (80 cm height and 160 cm width) and wooden frame (2 m length, 8.5 cm wide and 30 cm height) attached with a ruler were placed over the test bin.

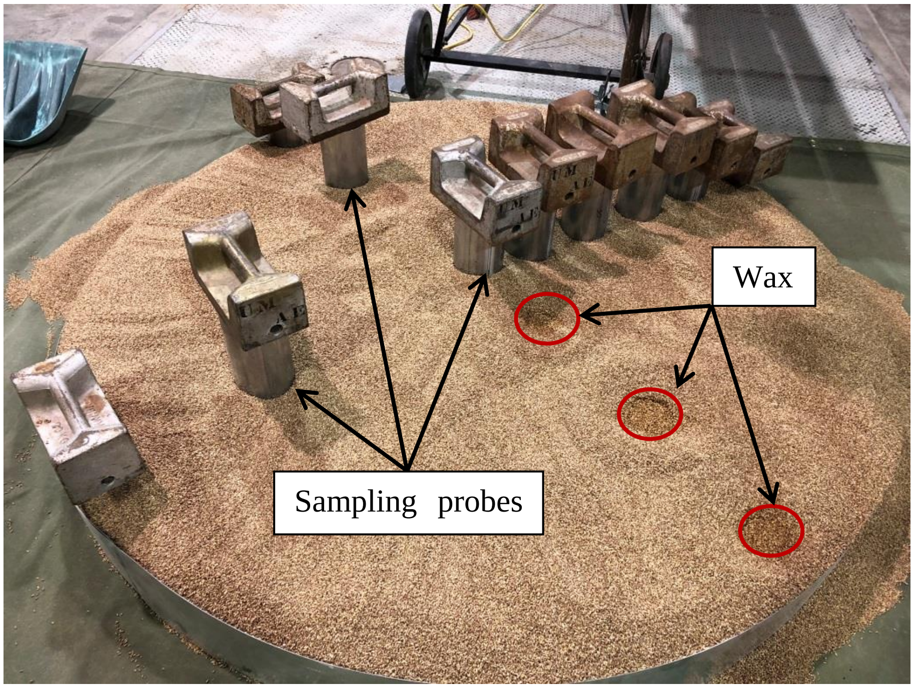

Fig. 3 Sampling locations.

The sampling probes were inserted into the pile manually at the following 6 locations along a radius: 0, 18.8, 37.6, 56.4, 75.2 and 94 cm from the centre. Four more probes were inserted along two more radii, corresponding to 56.4 and 94 cm distance from the centre. Cast iron weights were placed over the probes to reduce any disturbance while unloading the grain (Fig. 3). After about 12 h of the wax solidification, the grain around the sampling probes was removed by shovel and fed into the three dimensional vibratory separator through auger no. 3 (3.25 m length and 9.5 cm diameter), the wax samples were marked to indicate the direction towards the centre and taken out from the pile (Fig. 4). Visual analysis was done and photographs of the pieces of the wax-solidified grain were taken. The sampling probes were steel pipes (12.7 cm outer diameter and 50 cm height) with 2.2 mm thickness, and there were two slots at 5 and 20 cm from the bottom of the pipes. After two metal plates were inserted into the slots, the grain between the two plates was sampled separately (Figs. 5 and 6). The test bin was emptied and cleaned for the next trial. The three dimensional vibratory separator separated the grain mixture into three fractions: 1) mixture of soybean and kidney bean, 2) wheat, and 3) canola with broken wheat and fine particles. The mixture of soybean and kidney bean was manually separated by using No. 3 (6.7 mm opening) hand sieve. Canola was manually separated from the broken wheat and fines by using No. 10 (2.00 mm) and No. 14 (1.41 mm) sieves. The overflow of No. 10 sieve was broken wheat and the underflow of No. 14 sieve was fine particles. The broken wheat and fine particles were discarded and the grains were used again for the next treatment or replicate.

Fig. 4 Taking out wax samples. Insert: Marking the direction towards centre.

Fig. 5 Inserting plates into the sampling probes.

Fig. 6 Collecting grain sample in a tray.

3.6 Sample analysis

The weight of each grain sample was measured. As the volume of the grain sample inside the metal probe was known, bulk density of the samples was calculated. The wheat, canola, soybean, and kidney bean in each grain sample were manually separated by using No. 4, 8, 10, and 14 sieves with opening of 4.75, 2.36, 2.00 and 1.41 mm, respectively. The percentages of each grain in a sample were determined after the grain mass was weighed using balances with precision of 0.1 and 0.001 g for wheat and other grains, respectively. The percentages of each grain in each sample were then normalized as follows:

$$Normalized\ value = \frac{Percentage\ of\ the\ grain\ in\ the\ sample}{Average\ percentage\ of\ the\ grain\ in\ the\ trial}$$

Normalized value >1 at a location indicates the grain at the location is more than the average percentage, and vice versa.

3.7 Statistical analysis

To study the effect of drop height, percentage of other grains in the grain mixture before loading into the test bin and the type of other grain on the distribution of other grains after loading, two sample locations tests and empirical distribution function (EDF) statistics were used (SAS, 2018). The Wilcoxon and Median test tested for difference in locations and the Kolmogorov-Smirnov (KS) test tested for difference in distribution. Pairwise comparisons for amounts of other grain at each location was done using Tukey’s test. If the tested factor did not significantly influence the distribution of the other grains inside the test bin, the data associated with this factor were pooled.

4 Results and discussion

4.1 Wax study

The orientation of grains at three different locations was visually analysed (Fig. 7). Wheat, kidney beans and soybeans had their major dimensions along the radius of the pile at all the three locations. The videos showed that when the wheat and kidney bean kernels slide, their major dimension was along the radius of the pile. This orientation could be the reason for higher air flow resistance offered by the mixture in vertical airflow than horizontal airflow (Kumar and Muir, 1986).

Fig. 7 Image of the grain kernels taken perpendicular to the radius (left) and along the radius (right).

The orientation of canola grains could not be clearly observed on the surface of the wax samples. The samples have been stored in mice-proof containers for later analysis.

4.2 Bulk density

The bulk density at all the locations (for 80 and 240 cm drop height) at 0% other grains was higher than 3 and 6% other grains but the difference was not statistically significant (Fig. 8). As the bulk density of wheat is higher than other grains (Jayas and Cenkowski, 2014), adding more canola, kidney bean and soybean decreased the bulk density.

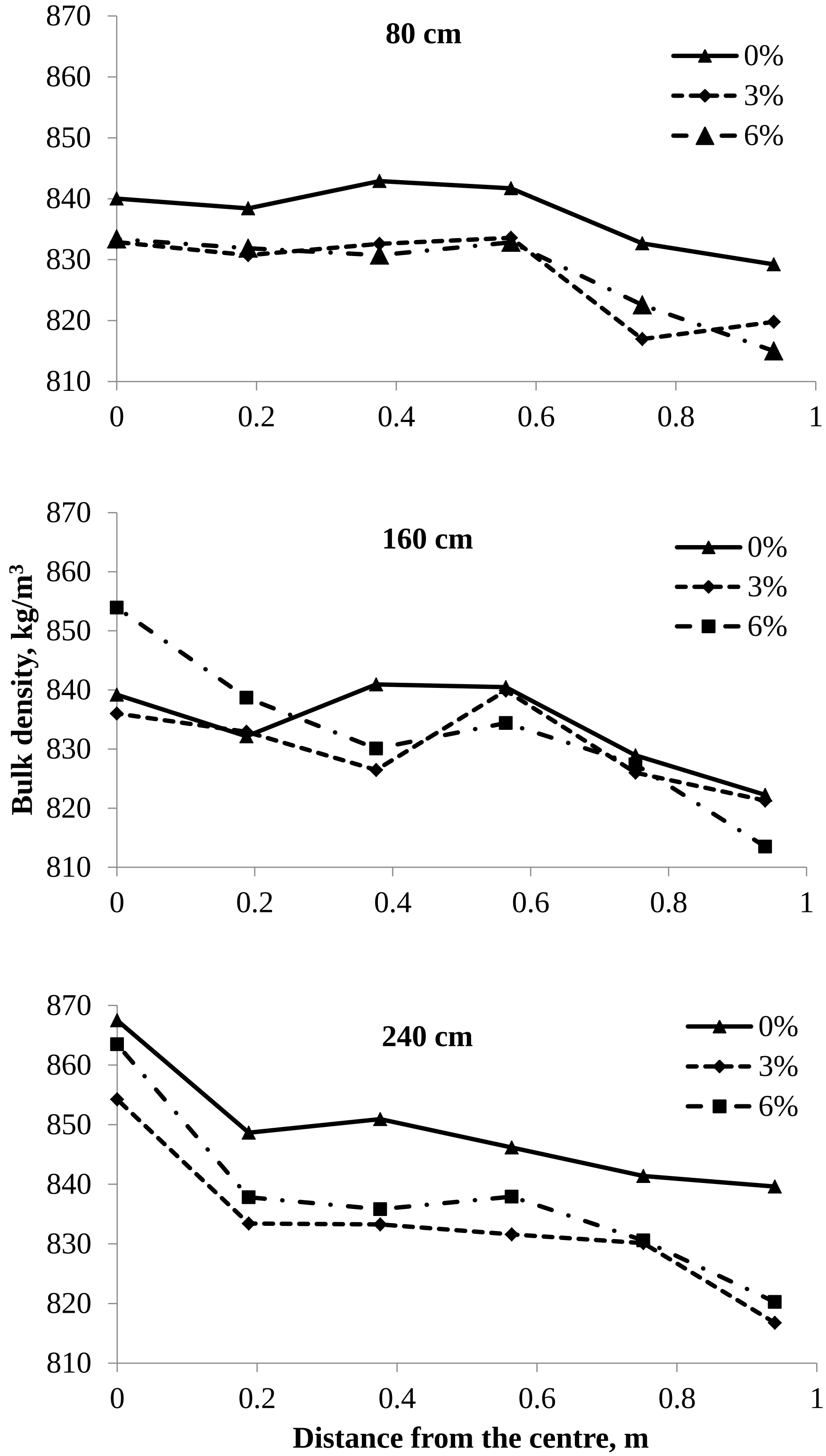

Fig. 8 Distribution of bulk density (kg/m^3) of the grain mixture at different drop heights. In the graph, the number before the '%' is the percentage of the other grains.

The bulk density (normalized value) at each location and the trend of bulk density distribution at 0, 3 and 6% other grains was not significantly different at all three percentages of other grains (Table 2) (Fig. 9). So the data for 0, 3 and 6% were pooled to test the difference due to drop height (Fig. 10) (Table 3).

Table 2 Results of two sample location tests and EDF statistics for distribution of bulk density (normalized values) at different drop heights (80, 160 and 240 cm) and different percentages of other grains (0, 3 and 6%).

Experiments [a]		Wilcoxon		Median		Kolmogorov-Smirnov	
		Z	P>Z	Z	P>Z	KSa	P>KSa
80-0	80-3	-0.72	0.4709	-0.49	0.6247	0.37	0.9992
80-0	80-6	0.58	0.5653	0.42	0.6759	0.20	1.0000
80-3	80-6	-0.14	0.8894	0.03	0.9721	0.18	1.0000
160-0	160-3	0.71	0.4788	0.71	0.4747	0.41	0.9963
160-0	160-6	0.71	0.4788	0.71	0.4747	0.41	0.9963
160-3	160-6	0.00	1.0000	0.00	1.0000	0.00	1.0000
240-0	240-3	-0.47	0.6361	0.00	1.0000	0.39	0.9981
240-0	240-6	-0.16	0.8758	0.00	1.0000	0.22	1.0000
240-3	240-6	-0.34	0.7354	0.00	1.0000	0.39	0.9981

[a] Comparison between two experiments. The number before the dash represents the drop height (80, 160 or 240 cm) and the number after the dash represents the percentage of other grains (0, 3 or 6%).

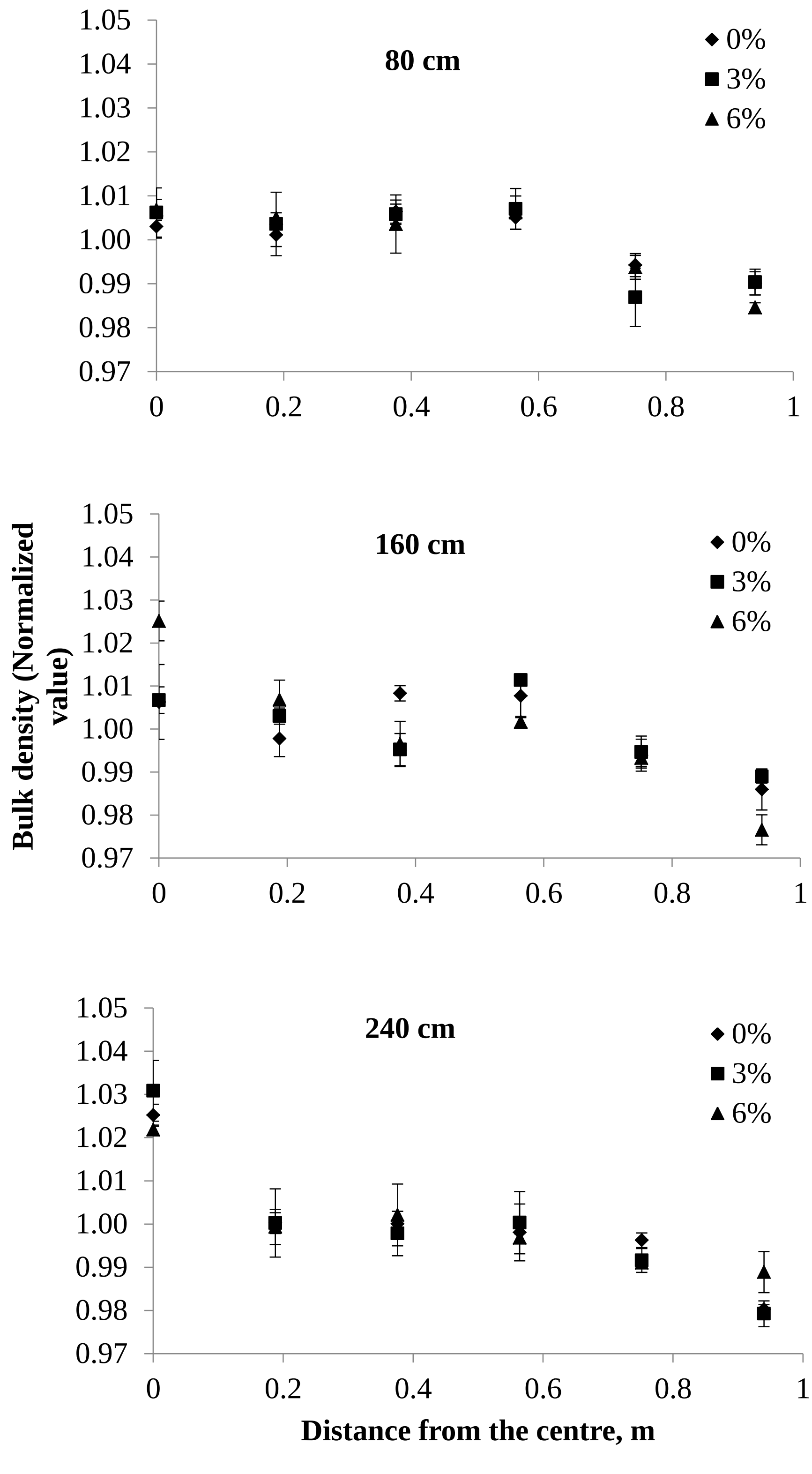

Fig. 9 Distribution of bulk density (normalized value) of the grain mixture at different drop heights. In the graph, the number before the '%' is the percentage of other grains.

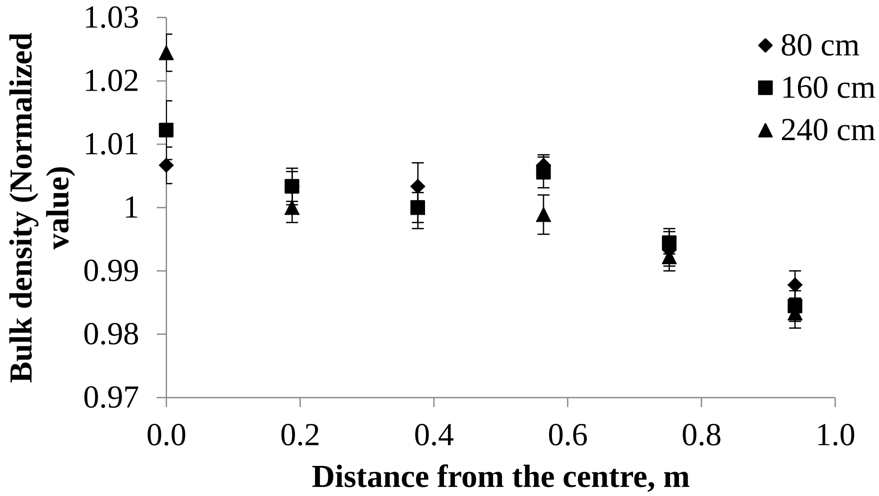

Fig. 10 Distribution of bulk density (normalized value) of the grain mixture at different drop heights. The values for each drop height are mean values of 0, 3 and 6% other grains.

Table 3 Results of two sample location tests and EDF statistics for distribution of bulk density (normalized value) for different drop heights (80, 160 and 240 cm).

Drop height [a], cm		Wilcoxon		Median		Kolmogorov-Smirnov	
		Z	P>Z	Z	P>Z	KSa	P>KSa
80	160	-0.37	0.7111	-0.25	0.7994	0.20	1.0000
80	240	-1.08	0.2803	-0.77	0.4423	0.47	0.9786
160	240	-0.74	0.4612	-0.51	0.6110	0.33	0.9999

[a] Comparison between two drop heights.

The drop height did not have a significant effect on the distribution of bulk density (Table 3) which is similar to the study done by Chang et al. (1986) but contradictory to Parker et al. (2005). But the pairwise comparisons between each drop height for bulk density (normalized value) in individual locations showed that the bulk density at the centre significantly increased with drop height at 6% other grains (Table 4). Higher impact forces at the centre might have resulted in a higher compaction.

Table 4 Results of pairwise comparisons of drop height for bulk density (normalized value) using Tukey's test.

Drop height [a], cm		q	P
80	160	5.995	0.013*
80	240	7.864	0.004*
160	240	1.869	0.435

[a] Comparison between two drop heights.

4.2.1 Effect of moisture content

The experiment was conducted over a period of 40 days and the order of trials and the test weight of wheat are given in Table 5. The trials under 0% other grains were conducted first which were followed by trials under 3 and 6% other grains. The difference in moisture content of wheat between the first and last trial was 3.05% (w.b.). As bulk density is affected by change in moisture content, the higher bulk density values (kg/m^3) (Fig. 8) in the trials under 0% other grains might be the result of moisture loss of grains. The effect of moisture content on the distribution of other grains could be negligible in this study because: 1) the effect of the change in moisture content should be combined with the effect of adding other grains because adding other grains and the decrease in moisture content occurred at the same order; 2) the percentage of the other grains in the wheat mixture before loading did not significantly influence the distribution of the other grains; 3) the grains used were over-dried at the very beginning of this study, and slight moisture change should not significantly influence the segregation when grain was over-dried; and 4) if moisture content decrease did significantly influence the segregation, the pattern of distribution of the other grains should change, but this did not happen.

Table 5 Schedule of trials and test weight of wheat.

Percentage of other grains	Drop height (cm)	Test weight [a] (kg/m^3) (Mean ±S.E.)
0	80	407.3±0.4
	160	406.0±0.4
	240	405.7±0.5
3	80	-
	160	-
	240	-
6	240	404.6±0.4
	160	404.4±0.3
	80	404.2±0.2

[a] Each value is an average of three trials. The test weight was not measured for the trials under 3% other grains.

4.3 Canola

For all drop heights, more canola was found at the periphery than all other locations (Fig. 11). The effect of the percentage of other grains on the distribution of canola was not significant (Table 6). So, the normalized values at 3 and 6% other grains were pooled to test the effect of drop height (Fig. 12). The effect of drop height on the amounts of canola at different locations at 80 cm drop height is significantly different from 160 and 240 cm drop heights. There was no significant difference in the pattern of distribution between all drop heights (Table 7). The amount of canola at the centre significantly decreased with increasing drop heights (Table 8) at 3 and 6% other grains, accompanied by the increase at the periphery. These results indicated that the smaller grain kernels would tend to distribute at far locations from the center. This is contradictory with the results obtained by Parker et al. (2005). This might be due to the effect of bin size as the square bin used by Parker et al. (2005) had a side of 1 m which means the periphery of the bin is just 0.5 m away from the centre and more amount of canola grains would have bounced off the bin wall leading to lower amounts at the periphery.

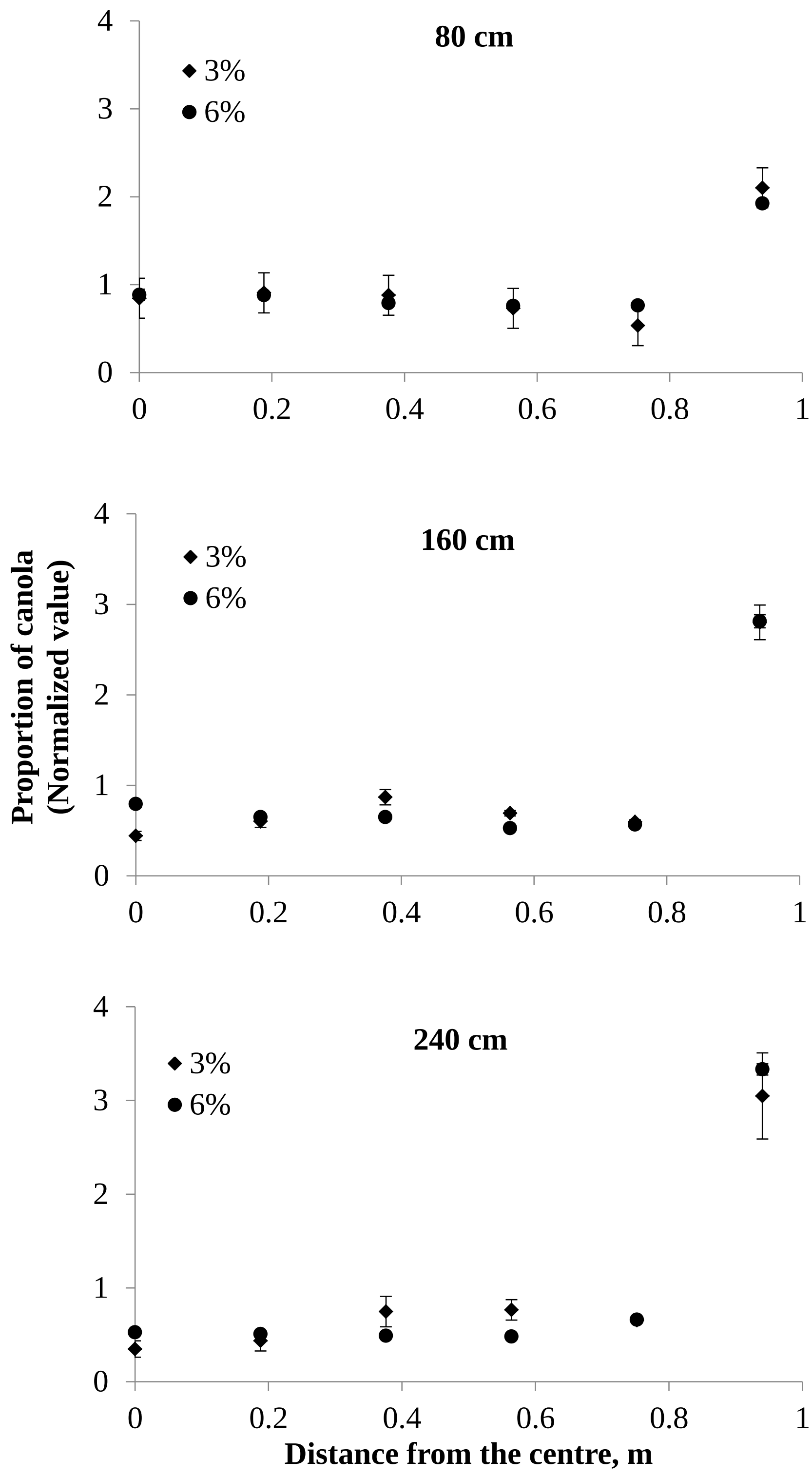

Fig. 11 Distribution of canola (normalized value) at different drop heights. In the graph, the number before the '%' is the percentage of the other grains.

Table 6 Results of two sample location tests and EDF statistics for distribution of canola (normalized value) at different drop heights (80, 160 and 240 cm) and different percentages of other grains (3 and 6%).

Experiments [a]		Wilcoxon		Median		Kolmogorov-Smirnov	
		Z	P>Z	Z	P>Z	KSa	P>KSa
80-3	80-6	0.11	0.9126	0.56	0.5723	0.40	0.9973
160-3	160-6	0.00	1.0000	0.00	1.0000	0.00	1.0000
240-3	240-6	-0.89	0.3741	-1.00	0.3173	0.24	1.0000

[a] Comparison between two experiments. The number before the dash represents the drop height (80, 160 or 240 cm) and the number after the dash represents the percentage of other grains (3 or 6%).

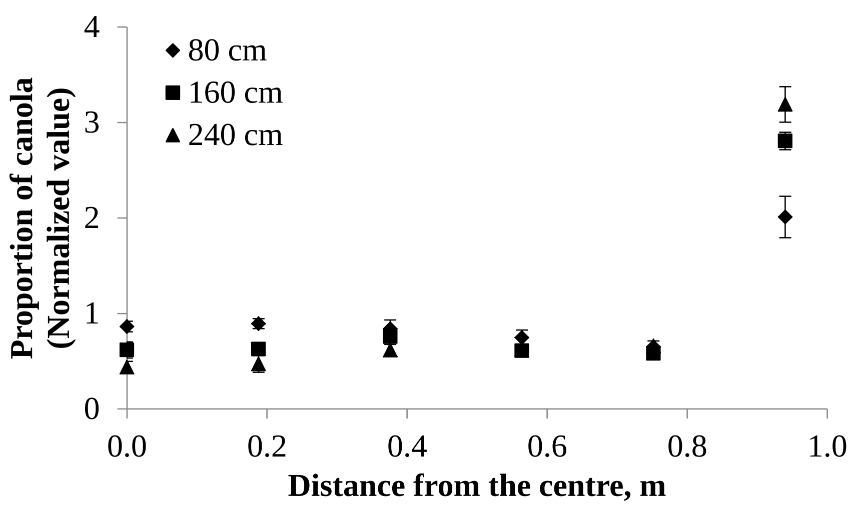

Fig. 12 Distribution of canola (normalized value) at different drop heights. The values for each drop height are mean values of 0, 3 and 6% other grains.

Table 7 Results of two sample location tests and EDF statistics for distribution of canola (normalized value) at different drop heights (80, 160 and 240 cm).

Drop height [a], cm	Wilcoxon		Median		Kolmogorov-Smirnov	
	Z	P>Z	Z	P>Z	KSa	P>KSa
80 vs 160	-2.28	0.0228*	-2.33	0.0197*	0.88	0.4100
80 vs 240	-2.15	0.0314*	-2.09	0.0363*	0.81	0.5360
160 vs 240	0.78	0.4328	0.85	0.3954	0.15	1.0000

[a] Comparison between two experiments.

Table 8 Results of pairwise comparisons of drop height for amount of canola (normalized value) at the central and the peripheral locations using Tukey's test.

Percentage of other grains	Centre				Periphery			
	Drop height [a], cm		q	P	Drop height [a], cm		q	P
3	80	160	4.554	0.049*	80	160	Not significantly different	
	80	240	5.604	0.018*	80	240		
	160	240	1.050	0.877	160	240		
6	80	160	2.053	0.376	80	160	16.276	<0.001*
	80	240	8.171	0.003*	80	240	25.759	<0.001*
	160	240	6.118	0.012*	160	240	9.483	0.001*

[a] Comparison between two drop heights.

The mechanism behind the high amounts of canola at the peripheral location might be the impact segregation (Mosby et al., 1996; de Silva et al., 2000), which we observed in the slow-motion videos during the loading.

At the beginning of the grain loading, when canola was dropped onto the cone of the grain pile, the impact forces from the wheat, kidney bean and soybean made the canola kernels to bounce away from the centre to the periphery. After a considerable pile was formed, the canola kernels which bounced to some locations before the periphery also reached the periphery of the pile by bouncing on the surface of the pile (Fig. 13). The normalized value at the peripheral location increased significantly with drop heights at 6% other grains (Fig. 12) (Table 8). When the drop height was increased, the impact forces on the canola grains might have increased which then caused more canola grains to bounce to the periphery.

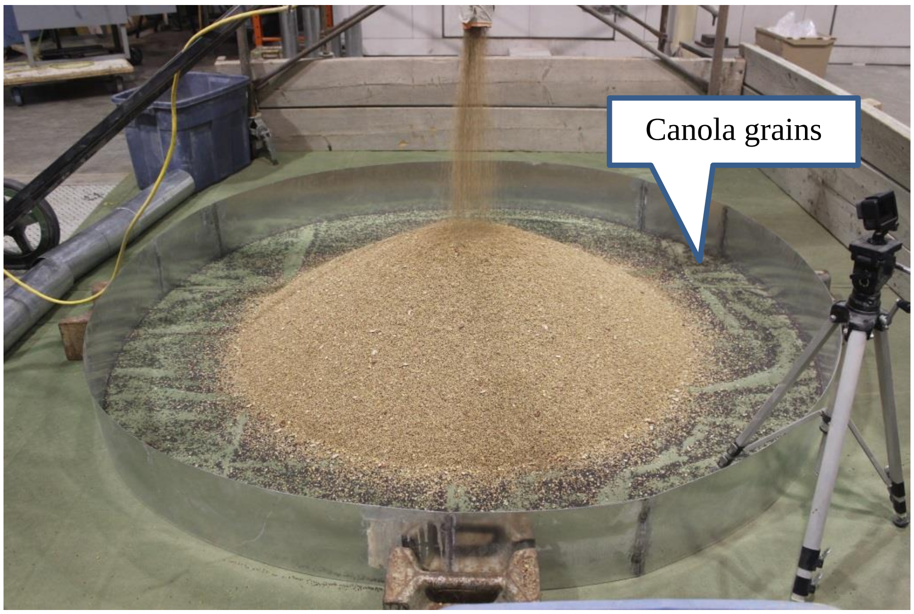

Fig. 13 Canola grains at the bin periphery due to impact forces.

Considering the relatively smaller size of canola than other grains in this study, there should have been a considerable sieving effect. From the videos, we observed only a small amount of canola on the surface of the pile slowly percolated inside. This might be because most of the canola grains experienced impact forces at the centre and bounced to the periphery. If the size of the bin was larger, the canola grains would have bounced and came to rest at some location before the periphery and thus had more chances of experiencing the sieving effect. It should be noted, the trend for the canola distribution might have been different for a larger bin.

4.4 Kidney bean and soybean

The distribution of kidney bean and soybean was similar and so they are discussed together (Fig. 14). The amount of kidney bean and soybean and their pattern of distribution have not been significantly affected by the percentage of other grains (Table 9). The data for kidney bean and soybean at different percentages of other grains were pooled to test the significance of the effect of drop height. The drop height did not have a significant effect on both the amount of kidney bean and soybean at different locations and their distribution (Table 10) (Fig. 15). The results indicated that larger grains are more likely to get more concentrated from the centre to mid locations of the bin. This is contradictory to Parker et al. (2005) where the amounts of soybean near the wall and the corners (in a square bin) were higher than that at the center. This could be because of the difference in the grain flow rate used in the study because the rolling effect is predominant when the rate of filling the bin is low.

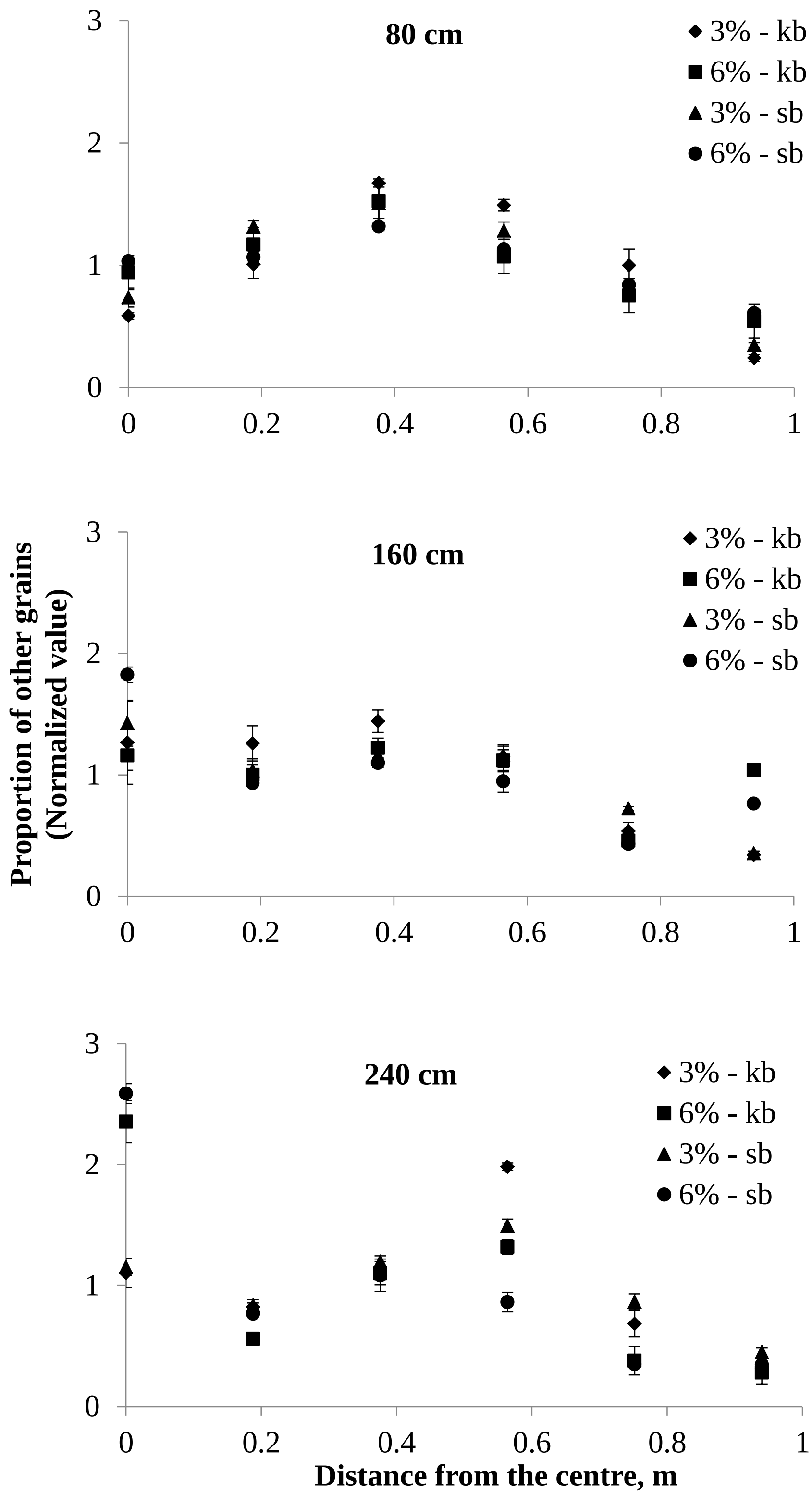

Fig. 14 Distribution of kidney bean (kb) and soybean (sb) at different drop heights. In the graph, the number before the '%' is the percentage of the other grains.

Table 9 Results of two sample location tests and EDF statistics for distribution of kidney bean and soybean (normalized values) for different drop heights (80, 160 and 240 cm) and different percentages of other grains (3 and 6%).

Experiments [a]		Wilcoxon		Median		Kolmogorov-Smirnov	
		Z	P>Z	Z	P>Z	KSa	P>KSa
Kidney bean							
80-3	80-6	0.71	0.4784	0.52	0.6024	0.22	1.0000
160-3	160-6	0.76	0.4482	0.75	0.4557	0.46	0.9848
240-3	240-6	1.20	0.2316	1.23	0.2170	0.64	0.8136
Soybean							
80-3	80-6	0.79	0.4306	0.51	0.6089	0.61	0.8552
160-3	160-6	-0.51	0.6074	-0.34	0.7336	0.32	1.0000
240-3	240-6	1.28	0.2005	1.22	0.2223	0.58	0.8891

[a] Comparison between two experiments. The number before the dash represents the drop height (80, 160 or 240 cm) and the number after the dash represents the percentage of other grains (3 or 6%).

Table 10 Results of two sample location tests and EDF statistics for distribution of kidney bean and soybean (normalized values) for different drop heights (80, 160 and 240 cm).

Drop height [a], cm		Wilcoxon		Median		Kolmogorov-Smirnov	
		Z	P>Z	Z	P>Z	KSa	P>KSa
Kidney bean							
80	160	0.31	0.7570	0.18	0.8579	0.45	0.9875
80	240	-0.98	0.3292	-0.19	0.8508	1.16	0.1367
160	240	-0.66	0.5092	-0.07	0.9428	0.73	0.6639
Soybean							
80	160	-0.66	0.5065	-0.21	0.8348	0.62	0.8436
80	240	-1.23	0.2194	-0.55	0.5853	1.01	0.2590
160	240	0.47	0.6363	0.36	0.7154	0.36	0.9994

[a] Comparison between two drop heights.

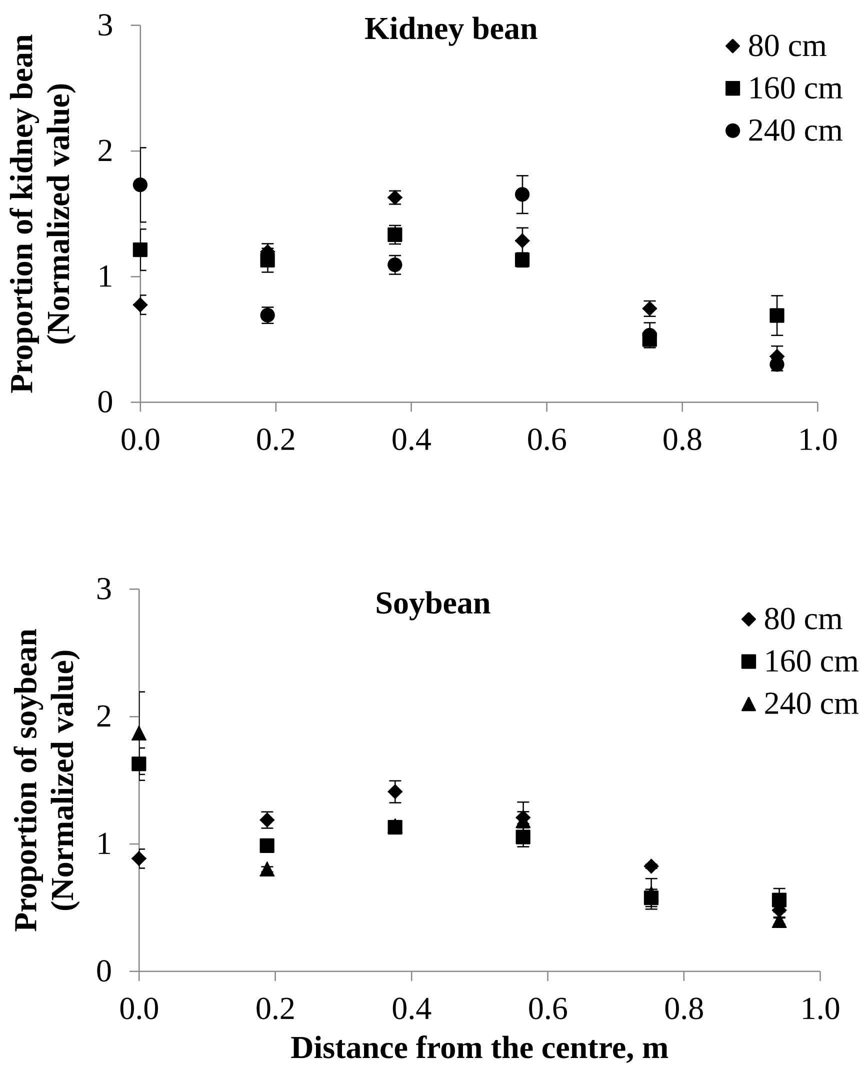

Fig. 15 Distribution of kidney bean and soybean (normalized value) at different drop heights. The values for each drop height are mean values of 0, 3 and 6% other grains.

The major mechanism found in the distribution of kidney bean was embedding and sliding whereas the distribution of soybean was controlled by embedding and rolling effects. The amount of kidney bean and soybean at the centre increased with drop height (Fig. 15) (Table 11). This might be because the embedding effect was more intense at higher drop heights.

Table 11 Results of pairwise comparisons of drop height for amount kidney bean and soybean (normalized value) at the centre using Tukey's test.

Percentage of other grains	Drop height [a], cm		Kidney bean		Soybean	
			q	P	q	P
3	80	160	Not significantly different		5.536	0.019*
	80	240			3.345	0.121
	160	240			2.192	0.335
6	80	160	1.764	0.4710	13.150	<0.001*
	80	240	11.376	<0.001*	25.785	<0.001*
	160	240	9.612	0.001*	12.635	<0.001*

[a] Comparison between two drop heights.

The sliding and rolling effects were predominant on the surface of the pile. It was observed in the videos that when the kidney bean and soybean grains were dropped onto the pile, the grains that did not get embedded at the apex were pushed away from the centre by the impact force of the falling stream of grains and then rolled/slid on the surface of the pile. When the pile had grown considerably larger, not all the grains rolled/slid continuously from the apex to the periphery of the pile. Sometimes the grains stopped moving at some mid location and then when it was hit by the other grains behind, it moved again and reached the periphery.

There was a peak in the normalized value of kidney bean and soybean at around the third (0.376 m) and the fourth (0.564 m) sampling location from the centre (Fig. 14). An interesting mechanism was observed during the pile formation which might be the reason for these peaks. After a considerable pile was formed, the filling angle of repose of the pile around the apex was not constant but was changing. As the grain fell down on the pile, another small pile kept building up on the top of the existing pile with a higher angle of repose and it collapsed after a certain point. When it collapsed, the grains constituting the smaller pile slid over the existing pile, regaining the original angle of repose. The apex became flatter, the height of the pile was reduced and a new pile started to build up. In this process, it was observed in the videos that when the pile was building up, kidney beans and soybeans slid and rolled down from the top of the pile due to a higher angle of repose. When the pile collapsed and the angle of repose was reduced, the grains stopped moving away from the centre for a while. Most of the grains that were already midway on the pile's surface stopped moving as well. When a new pile was formed and the succeeding grains moved down and some soybean and kidney beans on the surface got buried under the new grains. Also, it was noted that when the top pile collapsed and the layers slid, the grains in the centre were pushed away. This mechanism would have caused a high amount of kidney bean and soybean in the mid locations. This effect could be more easily seen at the lowest drop height (in the video) as there was less impact force from the falling grain and so the secondary pile steadily built up. Also, the sliding of grain caused by the collapse of the secondary pile was not simultaneous in all directions. This effect might be similar to the "avalanches" as described by De Silva et al. (2000).

4.4.1 Effect of shape

The difference between the distribution of kidney bean and soybean can be seen in Fig. 14. At all combinations of drop height and other grains, the normalized value of soybean at the centre was always higher than that of kidney bean. This could be attributed to the shape and the comparatively smaller size of soybean. The soybean grain could be embedded at the apex of the pile more easily than kidney bean as the latter was flat and longer than the former which made it comparatively more difficult to get embedded into the wheat grains.

4.5 Effect of grain type

The normalized values for 3 and 6% other grains were pooled to study the effect of grain type on the distribution of other grains at each drop height (Fig. 16). The amount of canola and its distribution pattern was significantly different from that of kidney bean and soybean at all three drop heights (Table 12). The median value of the amount of canola was not significantly different from that of kidney bean and soybean only at 160 and 240 cm drop heights. There was no significant difference between the distribution of kidney bean and soybean at all three drop heights.

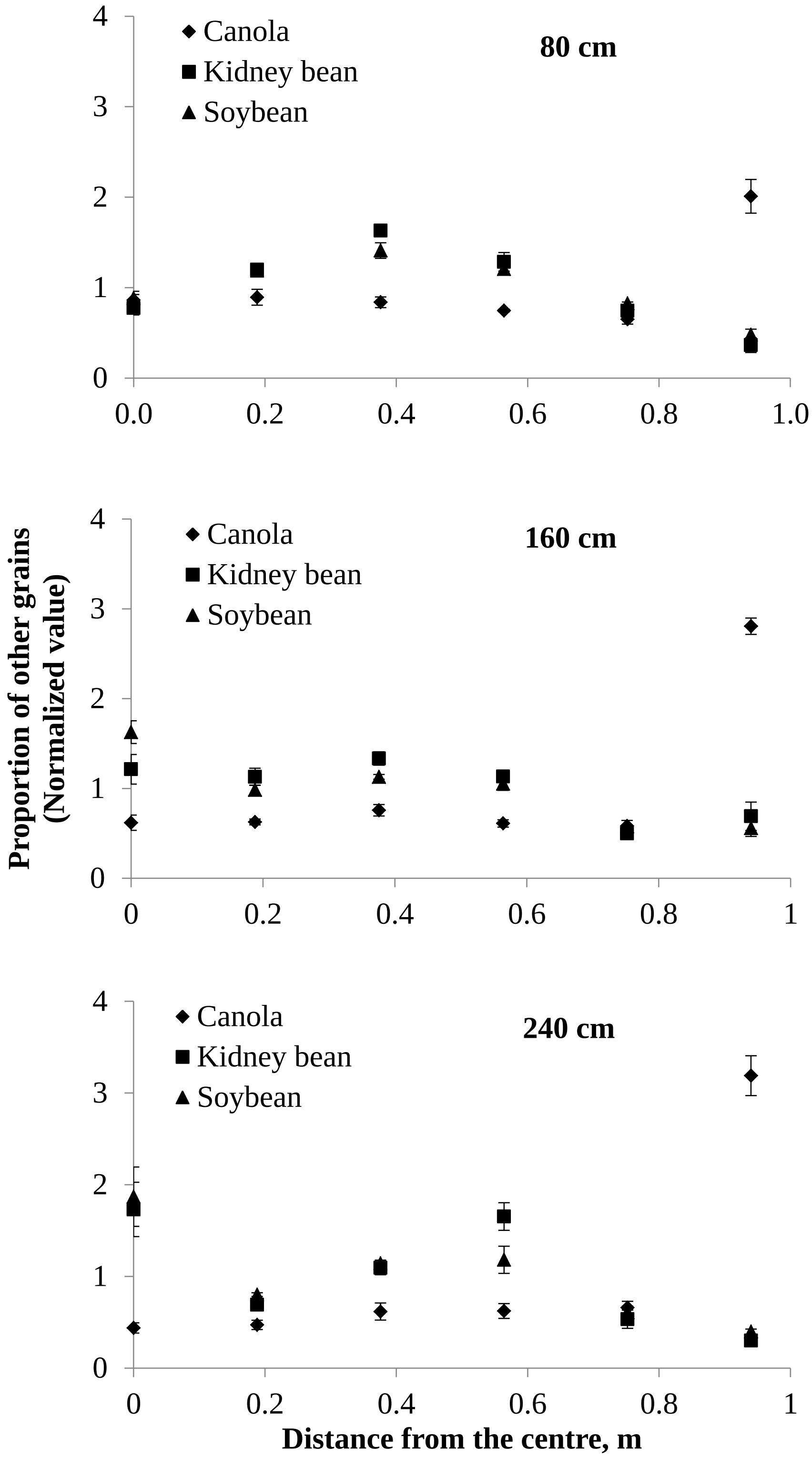

Fig. 16 Distribution of other grains (normalized value) at different drop heights. The values for each drop height are mean values of 3 and 6% other grains.

Table 12 Results of two sample location tests and EDF statistics for distribution of other grains (normalized value) at different drop heights (80, 160 and 240 cm).

Experiments [a]	Wilcoxon		Median		Kolmogorov-Smirnov	
	Z	P>Z	Z	P>Z	KSa	P>KSa
80 cm						
Canola vs kidney bean	2.03	0.0424*	1.43	0.1538	1.70	0.0064*
Canola vs soybean	2.24	0.0253*	1.61	0.1082	1.70	0.0064*
Kidney bean vs soybean	0.62	0.5360	0.37	0.7106	0.32	1.0000
160 cm						
Canola vs kidney bean	4.59	<0.0001*	4.88	<0.0001*	2.56	<0.0001*
Canola vs soybean	4.85	<0.0001*	5.06	<0.0001*	2.71	<0.0001*
Kidney bean vs soybean	-0.85	0.3953	-0.38	0.7043	0.50	0.9652
240 cm						
Canola vs kidney bean	5.22	<0.0001*	5.62	<0.0001*	2.87	<0.0001*
Canola vs soybean	5.30	<0.0001*	5.59	<0.0001*	2.87	<0.0001*
Kidney bean vs soybean	0.69	0.4907	0.50	0.6231	0.49	0.9718

[a] Comparison between two experiments.

5 Conclusions

1. The major dimension of wheat, kidney bean and soybean was found to be aligned along the radius of the pile.
2. The distribution of bulk density was not significantly affected by drop height and percentage of other grains.
3. Smaller and spherical grains like canola tended to get distributed far from the centre. The percentage of other grains did not have a significant effect on canola distribution, whereas the drop height had a significant effect on the amount of canola in different locations.
4. The major mechanism behind the distribution of canola could be impact segregation.
5. Larger grains like soybean and kidney bean tended to get distributed closer to the centre and mid locations of the bin. The percentage of other grains and the drop height did not have significant effect on the distribution of kidney bean and soybean.
6. The “avalanches” and embedding effects could be the mechanisms behind the distribution of kidney bean and soybean. Also sliding and rolling mechanisms were observed in kidney bean and soybean, respectively.
7. The amounts of canola at different locations and its distribution pattern were significantly different from that of kidney bean and soybean.

6 Recommendations for future research

1. Experiments can be conducted for different levels of grain moisture content and bin size and their effects can be studied.
2. Experiments can be done using grains that differ only by size, shape or density to investigate the individual effect of those physical properties.

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Appendix A: Raw data for bulk density, canola, kidney bean and soybean

Table A-1 Bulk density (kg/m^3) data for 0% other grains at different drop heights.

Distance from the centre, m	Bulk density (kg/m^3)		
	Replicate 1	Replicate 2	Replicate 3
80 cm			
0.940	837.56	827.44	822.67
0.752	831.39	836.72	829.89
0.564	838.89	847.72	838.50
0.376	856.67	842.94	829.06
0.188	835.06	838.33	841.83
0.000	834.61	844.33	841.11
160 cm			
0.940	818.67	820.89	827.22
0.752	836.06	820.33	830.39
0.564	852.83	833.83	834.72
0.376	845.78	840.39	836.61
0.188	842.28	824.00	830.17
0.000	831.17	849.94	836.50
240 cm			
0.940	829.61	867.00	822.22
0.752	830.61	865.78	827.78
0.564	843.33	862.83	832.39
0.376	837.28	883.44	832.06
0.188	826.22	888.50	831.28
0.000	858.00	891.17	853.39

Table A-2 Amount of canola (g) in the sample for different percentages of other grains (3 and 6%) and drop heights (80, 160 and 240 cm).

Distance from the centre, m	Amount of canola in the sample, g					
	3%			6%		
	Replicate 1	Replicate 2	Replicate 3	Replicate 1	Replicate 2	Replicate 3
80 cm						
0.940	11.659	7.161	11.583	39.841	32.523	32.828
0.752	3.173	2.350	2.334	15.214	13.517	13.234
0.564	4.422	3.490	3.076	15.041	13.585	13.557
0.376	5.635	5.107	2.699	16.311	14.061	13.620
0.188	6.485	5.516	2.109	18.621	15.529	14.991
0.000	6.179	4.484	2.481	21.597	14.630	13.788
160 cm						
0.940	16.034	13.03	23.355	56.198	57.063	60.952
0.752	3.871	2.732	4.559	11.113	11.991	12.669
0.564	4.777	3.268	5.085	9.809	12.239	11.476
0.376	5.657	4.892	5.281	11.734	15.488	13.932
0.188	4.196	3.363	3.505	12.708	15.014	13.843
0.000	3.051	2.495	2.577	17.434	18.064	16.105
240 cm						
0.940	5.667	16.633	19.769	48.376	49.08	47.626
0.752	1.787	3.197	3.705	8.617	9.632	10.972
0.564	2.638	3.021	4.005	6.692	7.318	7.438
0.376	2.928	2.847	3.333	6.67	7.071	8.04
0.188	1.756	1.389	2.155	7.106	7.564	7.942
0.000	1.467	1.125	1.749	8.111	7.815	8.234

Table A-3 Amount of kidney bean (g) in the sample for different percentages of other grains (3 and 6%) and drop heights (80, 160 and 240 cm).

Distance from the centre, m	Amount of kidney bean in the sample, g					
	3%			6%		
	Replicate 1	Replicate 2	Replicate 3	Replicate 1	Replicate 2	Replicate 3
80 cm						
0.940	3.558	2.691	6.445	22.155	13.306	15.791
0.752	11.110	11.746	26.881	26.330	21.098	23.009
0.564	28.312	30.029	40.516	44.733	28.716	29.586
0.376	34.666	33.826	45.604	54.120	44.240	45.756
0.188	27.041	24.592	27.272	37.427	36.151	36.196
0.000	13.100	11.067	15.751	37.848	24.831	27.576
160 cm						
0.940	7.511	6.451	5.822	49.005	35.283	29.576
0.752	9.433	15.121	7.719	25.235	17.996	9.622
0.564	25.428	23.344	19.792	44.643	43.396	34.676
0.376	30.641	31.010	23.381	65.044	43.958	30.542
0.188	29.354	26.674	18.863	41.900	43.016	27.047
0.000	11.744	31.821	31.843	60.053	34.237	38.638
240 cm						
0.940	5.556	10.087	7.789	5.705	12.375	24.764
0.752	11.887	22.096	17.337	13.943	11.080	33.809
0.564	48.624	52.542	47.386	59.553	62.173	79.324
0.376	33.359	23.194	24.628	56.517	57.701	50.889
0.188	21.901	19.134	20.599	27.729	26.320	31.109
0.000	30.589	35.208	20.267	132.800	116.412	116.751

Table A-4 Amount of soybean (g) in the sample for different percentages of other grains (3 and 6%) and drop heights (80, 160 and 240 cm).

Distance from the centre, m	Amount of soybean in the sample, g					
	3%			6%		
	Replicate 1	Replicate 2	Replicate 3	Replicate 1	Replicate 2	Replicate 3
80 cm						
0.940	6.160	6.632	9.039	27.383	21.576	24.034
0.752	14.798	15.561	19.745	36.774	31.443	33.170
0.564	23.092	24.791	33.820	47.799	43.792	46.328
0.376	29.365	35.513	29.215	53.408	53.781	52.918
0.188	25.481	24.704	33.100	40.553	43.285	45.974
0.000	16.807	12.136	17.552	43.271	41.228	41.567
160 cm						
0.940	5.795	6.078	5.766	33.267	29.548	26.472
0.752	13.528	12.286	10.605	16.723	16.738	17.430
0.564	24.210	18.147	17.283	37.410	45.124	31.013
0.376	22.118	19.649	16.893	51.353	40.570	39.336
0.188	16.598	21.714	14.464	42.189	38.927	31.471
0.000	19.181	27.773	24.952	87.247	68.740	68.324
240 cm						
0.940	7.172	7.805	6.258	12.484	14.968	15.295
0.752	11.309	14.718	15.6258	12.473	13.978	17.379
0.564	24.346	22.837	24.720	38.999	34.910	34.023
0.376	19.717	19.757	18.179	40.568	50.449	45.423
0.188	13.501	13.298	13.451	29.884	34.353	32.340
0.000	16.686	18.852	21.571	95.585	117.459	123.997

Appendix B: Web links for videos

The videos captured during the experiment were uploaded to YouTube and MSpace (University of Manitoba thesis repository).

Table B-1 Title of the uploaded videos for each segregation mechanism

Mechanism	Title of the YouTube video
Impact segregation (canola)	Impact segregation of canola in bulk wheat
Sliding/ rolling (Kidney bean and soybean)	Segregation of kidney beans and soybeans in bulk wheat - sliding/rolling
Avalanches (Kidney bean and soybean)	Segregation of kidney beans and soybeans in bulk wheat - avalanches