Segregation of Dockage and Foreign Materials in Wheat during Loading into a 10-meter Diameter Bin

by

Alireza Salarikia

A thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

Department of Biosystems Engineering

University of Manitoba

Winnipeg, Canada

ABSTRACT

Harvested bulk grains contain many impurities, categorized into dockage and foreign materials (DFM), mixed with sound grain kernels. Segregation of the DFM particles is an unavoidable phenomenon in bulk grain during handling, transportation and storage that causes many problems such as uneven airflow distribution during aeration and drying. In this study, the radial distribution of DFM, and shrunken and broken kernels (SBK) was determined during loading of grade two Canada Western Red Winter (CWRW) wheat at 12.2 ± 0.4% moisture content (wet basis) in a 10-m diameter flat-bottom cylindrical bin. Wheat was loaded vertically into the bin from five different drop heights (1.6, 2.5, 3.4, 4.3 and 5.2 m). In-situ filling angle of repose of wheat was measured after each drop height loading. Samples were collected from the top and bottom of a sampling tube (29 cm diameter and 50 cm deep) inserted vertically at five different locations (0.00, 1.25, 2.50, 3.75 and 5.00 m horizontal distance from the center) along three radii of the bin for each drop height. The impurities from each collected sample were divided into five different categories with different sizes (other grains, other particles, shrunken and broken wheat kernels, fine particles, and dust and fragments) by sieving using a sieve shaker. Impurities larger and smaller than wheat kernels were categorized as large impurities and small impurities, respectively.

No vertical segregation was observed between top and bottom samples from each sampling location. Drop height significantly influenced the radial distribution of fine particles and dust and fragments; however, it did not affect the distribution of other grains and other particles. The average in-situ filling angle of repose was 22.9 ± 1.4°. Fine particles and dust and fragments mainly accumulated in the center, while shrunken and broken wheat kernels accumulated mostly near the wall of the bin. Both true density and test weight (bulk density) of unclean wheat and test weight of clean wheat significantly changed along the radius of bin.

Test weight of unclean wheat was minimum in the center and close to the wall of bin. Drop height did not influence true density and test weight of clean and unclean wheat. Porosity, thousand kernel weight, kernel dimensions, and sphericity of wheat were similar at different radial locations of bin as well as with different drop heights.

DEDICATION

Dedicated to the memory of my mother and my father,

who always believed in my ability to be successful in the academic arena.

You are gone but your belief in me has made this journey possible.

Forever you remain in my soul.

ACKNOWLEDGEMENTS

I would like to first express special gratitude to my supervisor, Dr. Fuji Jian, for his kindly guidance and encouragement during my studies. I am very thankful to my co-supervisor Dr. Digvir S. Jayas for his support and my committee members Dr. Ying Chen and Dr. Qiang Zhang who also gave me great knowledge during my coursework. I thank Dr. Francis Zvomuya and Dr. Stefan Cenkowski for the courses that enriched me with the knowledge required for my research.

My deepest appreciation goes to Dr. Paul Fileds for his kindly advice and support. I would further like to thank to Dr. Jitendra Paliwal, Dr. Chyngyz Erkinbaev and Dr. Vincent Harvet for their valuable encouragement. I am also thankful to Kim Hamilton, Marcel Lehmann, Matt McDonald and Minami Maeda for their assistance. I am grateful to my friends Mehul, Vimala, Rahul and Vignesh.

I thank the Natural Sciences and Engineering Research Council (NSERC) of Canada and University Manitoba ‘GETS’ program for the financial support.

Lat but not least, a special thank you to my family. Words cannot express how grateful I am to my beloved wife, who believed in my potential and has made countless sacrifices to support me.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Common wheat or bread wheat (*Triticum aestivum* L.), which generally is referred to as wheat, is one of the most essential grains globally and is a worldwide staple food due to its rich source of carbohydrates and proteins (Shewry and Hey 2015). In 2018, more than 734 million tonnes of wheat were harvested from more than 214 million hectares in the world (FAO 2018). However, the demand for wheat is increasing in both developed and developing nations. Canada produced 31.8 million tonnes of wheat in 2018 (FAO 2018) and has an international reputation as a producer of high-quality wheat. This reputation is due to grading system regulated by the Canadian Grain Commission (CGC) under the Canada Grain Act. This grading system emphasizes on high cleanliness and uniform quality of grain (Canadian Grain Commission 2019). Having said that, Canada needs to secure and enhance its reputation in grain quality and increase its grain handling and storage capacity (Wang and Paliwal 2006).

Commercially stored bulk grain encompasses many materials in desired sound grain kernels. These materials (which include but are not limited to straw, rachis, internode, chaff, awn, un-threshed spikelet, shrunken and broken kernels, stone pieces, other grains (cereals), weed seeds, ergot, insect excreta, dead insects, bird dropping and animal filth) are considered undesired materials in grain mixture. Based on the literature, many different terminologies have been used to identify these materials intermixed with desired kernels in bulk grain, and some of these terminologies overlap each other. In this study, any undesired materials rather than sound grain kernels in bulk wheat except shrunken and broken kernels (SBK) will be referred to as DFM (dockage and foreign materials). Both DFM and SBK in bulk grains are reported in percentage by mass. In this study DFM includes stones, other large cereals such as corn and soybean, canola kernels, straw, internode, knuckle, rachis, spikelet, large chaff, wild oat kernels and stem, parts of other wild plants and dust. These DFM components can be categorized into two groups: particles larger than wheat kernels and particles smaller than wheat kernels.

The DFM components have different properties than main grain in size, shape, density, morphological properties and nutrition value. Grain may be handled and stored at different stages, from harvesting to consumption. Segregation in bulk materials is defined as the tendency of particles with similar physical properties to separate from other particles and collect together in one zone (De Silva et al. 2000). Figure 1.1 shows segregation in a mixture of particulate materials during loading. Segregation in bulk grain mixed with undesired materials occurs during handling and loading into bins (silos); therefore, the stored bulk grain may not be uniform (Jayas et al. 1987).

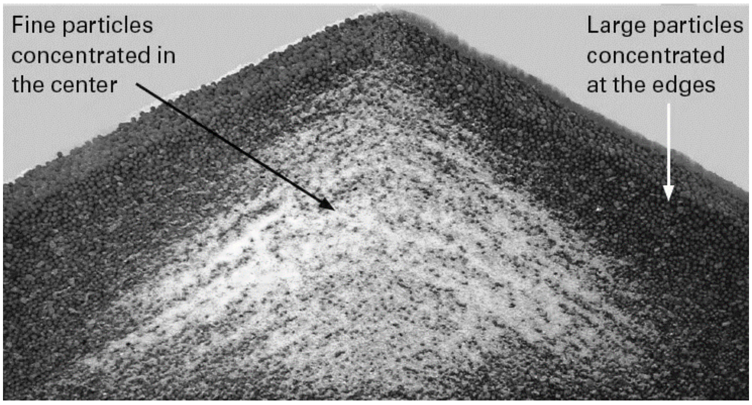

Fig. 1.1. Segregation in a mixture of particulate materials (Bates 1997).

Uneven distribution of DFM, as well as grain kernels with different physical properties, can cause many problems during storage, drying and aeration (Lawrence & Maier 2011; Nourmohamadi-Moghadami et al. 2020; Olatunde et al. 2016). Over-drying at high air velocity locations and grain with higher moisture content (MC) at the low airflow locations in the same bin are detrimental effects of uneven distribution of DFM (Jian et al. 2019). Moisture content and temperature are the most critical factors affecting the quality of grain during the storage period. Storing grain at unsafe moisture content or temperature can increase the risk of mold growth or insect multiplication (Olatunde et al. 2016). Forced air convection or aeration is vital in the safe storage of grain to even this non-uniform distribution of the grain moisture content and temperature. Segregation of DFM in a grain bin may change the uniformity of small intergranular pores, and consequently affects airflow resistance and air distribution in grain (Olatunde et al. 2016). As a result, a hot spot may develop in locations with low air circulation (high temperature and moisture content) (Prasad et al. 1978; Stephens and Foster 1978).

Another issue is that some stored grain insects prefer grain with a high percentage of DFM. Locations with a high percentage of DFM often provide more moist and ideal food for insects and therefore such locations are more likely to become highly infested by insects and deteriorate more quickly than clean grain (Jian et al. 2005; Mcgregor 1964). Based on the U.S. standards, wheat that contains more than 31 insect-damaged kernels in 0.1 kg of a wheat sample does not meet requirements for grading and is considered insect-infested (United States Department of Agriculture 2016). Insects also produce more dust in bins (Bian et al. 2015). The presence of dockage reduced significantly the effectiveness of fumigation in grain bins by increasing airflow resistance in some parts of the grain bin (Harein 1961) and also reduced the mortality of wheat insects when using diatomaceous earth (DE) (Kavallieratos et al. 2007). Dockage and broken kernels reduce effectiveness of insect control by absorbing fumigant vapors (Adam et al. 1994). Dockage with higher moisture content than the main grain in the bin, as well as broken kernels, provide suitable conditions for some stored grain fungi to grow. These components are the components in the bin that become infected by main stored grain fungi such as *Penicillium* species (Prasad et al. 1978).

Some grain, such as wheat or rye, can be contaminated by poisonous fungi such as ergot that cause ergotism in humans or livestock. Ergot is a stringent grading factor with tight grading tolerances. Also, finding an unexpected amount of weeds in bulk grain could be a sign that the farm is contaminated by weeds, and there may be some yield loss due to crop competition. A problem associated with grain trade is that uneven distribution of DFM in a bin could also affect the grade assigned to grain. Fine and dense particles and dust are mostly found in the center of a bin (Chang et al. 1986; Nourmohamadi-Moghadami et al. 2020). During unloading of grain from the bin bottom, due to the funnel flow of grain, the first few batches of grain unloaded will contain more fines and dust and, accordingly, low quality.

Grading is an essential tool to define the quality and, therefore, the market value of bulk grain. The initial quality of grain affects the procedure of processing and the quality of the end product, for example flour. One of the principal objectives of grading systems is to ensure the uniform quality of bulk grain. Grain may be handled and stored at different stages, from harvesting to consumption. Segregation of grain mixed with DFM occurs during handling and loading into bins; therefore, the stored grain in a bin or a grain truck may not be uniform (Jayas et al. 1987). The key for appropriately grading grain is to probe a good representative sample of grain from grain elevators or trucks. Underestimating the percentage of DFM in bulk grain will result in overpaying for the grain that consists of less desired grain than expected (Hagstrum et al. 2012). Most common bread wheat in Canada including Canada Western Red Winter (CWRW) wheat are divided into three grades based on the standards defined by Canadian Grain Commission (Table 1.1). In the United States, bread wheat is divided into five grades according to the United States Department of Agriculture (USDA) standards (United States Department of Agriculture 2016). However, the maximum limit of total foreign materials and shrunken and broken kernels in wheat grades 1, 2, and 3 in both Canada standards and U.S. standards are the same.

All these detrimental effects of presence or segregation of DFM in bulk grain including wheat, can potentially result in shortening the safe storage period of grain, affecting grain quality and grade evaluation, consequently downgrading the market value of the grain.

Hence, it is imperative to study and understand the distribution of DFM in bulk grain, especially in wheat. Moreover, segregation can be a detrimental issue in other industries such as food industry, pharmaceutical industry, soil science, coal and other mineral industries. For instance, in food processing, segregation has caused large variations in food product package due to varying bulk density (Prescott and Carson 2000). In pharmaceutics, a highly valuable batch of powder could be discarded just due to the variation in the number of active ingredients caused by segregation (Tang and Puri 2004). Having said that, segregations may prove to be useful for removing dockage from bulk grain using vibratory sifters. Hence, due to its important role in particulate materials, segregation has been studied over many years from various aspects in many industries (Shinohara 1997). Most studies that have been done so far on the distribution of DFM in bulk grain were in laboratory scale bins and also the DFM usually was added manually to the grain to desired level. Jian et al. (2019) implied that the segregation of DFM in bulk grain in large bins in real situation in farms should be studied. No study was found to determine radial distribution of shrunken and broken kernels in bin during loading wheat. This study was developed to fill these knowledge gaps. The main objective of this project was to study the distribution of DFM in graded wheat (with no extra dockage and undesired materials added) loaded into a 10-m diameter bin by following the loading methods typically used by most Canadian farmers. For this purpose, Canada Western Red Winter (CWRW) wheat graded number two (Table 1.1) was used. In addition, in-suit filling angle of repose of CWRW wheat during loading into bin was measured.

Table 1.1. Standards of quality and percentage of foreign materials and shrunken and broken kernels in different grades of Canada Western Red Winter (CWRW) wheat (Canadian Grain Commission 2019).

Standard of quality				**Foreign materials (%)**						**Shrunken and broken kernels (%)**		
Grade name	**Minimum test weight (g/0.5 L)**	**Minimum protein %**	**Degree of soundness**	**Ergot**	**Sclerotinia**	**Excreta**	**Stones**	**Matter other than cereal grains**	**Total**	**Shrunken**	**Broken**	**Total**
No. 1	386	11.0	Reasonably well matured, reasonably free from damaged kernels	0.04	0.04	0.01	0.03	0.2	0.4	3	3	3
No. 2	370	11.0	Fairly well matured, may be moderately frost-damaged, reasonable free from severely damaged kernels	0.04	0.04	0.01	0.06	0.3	0.7	3	5	5
No. 3	360	No minimum	May be frost-damaged, immature or weather-damaged, moderately free from severely damaged kernels	0.04	0.04	0.01	0.06	0.5	1.3	3	8	8
CW Feed	315	No minimum	Reasonably sweet, excluded from higher grades on account of lightweight or damaged kernels	0.10	0.10	0.03	0.10	1.0	10.0	No limit	13	No limit within broken tolerances

2. LITERATURE REVIEW

Bulk grain is a mixture of sound grain kernels, shrunken and broken kernels (SBK), and dockage and foreign materials (DFM). Both SBK and DFM have different physical properties compared to sound grain kernels. If DFM or SBK or both accumulate in some parts of the bin during loading, these could change the physical properties of stored bulk grain and might also result in grain spoilage. In this review, the definition of dockage, foreign materials and shrunken and broken kernels in wheat, the mechanisms of particle segregation in bulk grain, factors influencing segregation, the detrimental effects of segregation in bulk grain, and finally the major practical methods to minimize segregation in bulk grain are discussed.

2.1. Definition of dockage and foreign materials (DFM)

Many different terminologies in previous studies have been used to identify any materials intermixed with desired kernels in bulk grain, and some of these terminologies overlap each other. Under the Canada Grain Act (1985) by the Canadian Grain Commission (CGC), dockage is defined 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." This means that dockage is any material that can be removed from the grain by using approved cleaning equipment such as mechanical dockage tester or sieves so that the grain can be assigned the highest grade for which it qualifies (Canadian Grain Commission 2019; United States Department of Agriculture 2009). Also, "material other than grain of the same class that remains in the sample after the removal of dockage" is defined as foreign materials (Canadian Grain Commission 2019). Foreign materials may include other cereal or wild grains rather than desired grain such as oat (Dexter and D'Egidio 2012). Foreign materials cannot be easily removed from grain using normal cleaning procedures such as sieving or aspiration because they are usually the same size or weight as desired grain kernels (Dexter and D'Egidio 2012; Mercier 1989).

Dockage is not considered a grading factor and must be removed from sample before other grading factors are inspected (Mercier 1989). A graded grain may be sold with or without dockage. However, the percentage of dockage in grain triggers price discounts because dockage is considered a non-millable material especially in wheat that must be removed prior to flour milling to prevent damage to wheat flour quality and milling equipment (Mercier 1989). Some importers such as Japan has strict discounts on excessive dockage content (Mercier 1989). Cleaning to remove dockage before exporting grain is a way to reduce transportation costs, insect infestation and increase storability of grain; however the cleaning costs for exporters may be more than its benefits (Adam et al. 1994). So the exporters either need to meet customer specification for dockage or offer discounts (Dexter and D'Egidio 2012). Canadian grin is shipped dockage-free, i.e., dockage is removed before export (Dexter and D'Egidio 2012). On the other hand, the percentage of foreign materials in grain is an important grading factor in both Canada and U.S. grain standards, i.e., it can change the grade assigned to a grain and results in severe price reduction. Foreign materials may have negative effects on the storage condition and milling quality of grain and may need to be removed using sophisticated cleaning equipment before milling. For instance, they must be removed from durum wheat before semolina milling; otherwise it may affect semolina and pasta appearance (Dexter and D'Egidio 2012). Accordingly, Canada offers low limits of foreign materials in CWRW wheat (Table 1.1).

Other specific particles such as chaff and fine materials are not defined by Canadian Grain Commission, but some researchers have tried to distinguish them. Fine materials or fines are defined as smaller particles of DFM in bulk grain that can be separated by specific size sieves (Stroshine 1992). If these fine particles are smaller than 100 μm, they are referred to as dust (Jian et al. 2019). Narendran (2018) defined chaff based on CGC standards as "a type of dockage that includes loose hulls, empty seed pods, and knuckles that are readily removable by aspiration, handpicking, or other cleaning procedures."

Pieces of wheat kernels that are smaller than three-quarters of a whole kernel are considered broken kernels. If a whole kernel of wheat is shriveled and shrunken enough to pass through a specific size sieve (number No. 4.5 slotted sieve), it is considered as a shrunken kernel (Canadian Grain Commission 2019). Shrunken and broken kernels (SBK) are not considered as foreign materials in wheat; however, their distribution inside the grain bins is still important because they may affect the storage period or the quality of stored grain. The milling quality of durum wheat improved by removing SBK (Dexter and D'Egidio 2012). Therefore, SBK is considered a grading factor in both Canada and U.S. wheat standards. Shrunken and broken kernels can be removed from wheat by sieves or gravity tables (Dexter and D'Egidio 2012). No study was found on the distribution of SBK inside wheat bins. Shrunken and broken kernels do not include damaged kernels which are wheat kernels that are badly ground-damaged, badly weather-damaged, heat-damaged, diseased, frost-damaged, germ-damaged, insect-bored, mold-damaged, sprout-damaged, or otherwise materially damaged. Damaged kernels in wheat are determined after removing DFM from wheat by visual inspection of 15 g samples and comparing the suspicious kernels to the visual reference images (United States Department of Agriculture 2016). Therefore, damaged kernels are difficult to separate mechanically from grain.

In this study, Canada Western Red Winter (CWRW) wheat grade two was used, and the sum of dockage, foreign materials, and shrunken and broken kernels removed from wheat was referred to as total impurities, because the presence of all of them may affect wheat quality. Generally, DFM in bulk grain may include but not limited to chaff, straw, internode, knuckle, rachis (spikelet axis), awn spikelet, and unthreshed spikes of desired grain (Fig. 2.1) as well as other cereal grains, weeds, wild seeds, ergot, sclerotinia, excreta, dead insects, stones, earth pellets, soil particles, and grain dust. Unfortunately, despite the clear definition of dockage, foreign materials, and shrunken and broken kernels in wheat by CGC, some researchers have used dockage and foreign materials terminologies interchangeably and incorrectly.

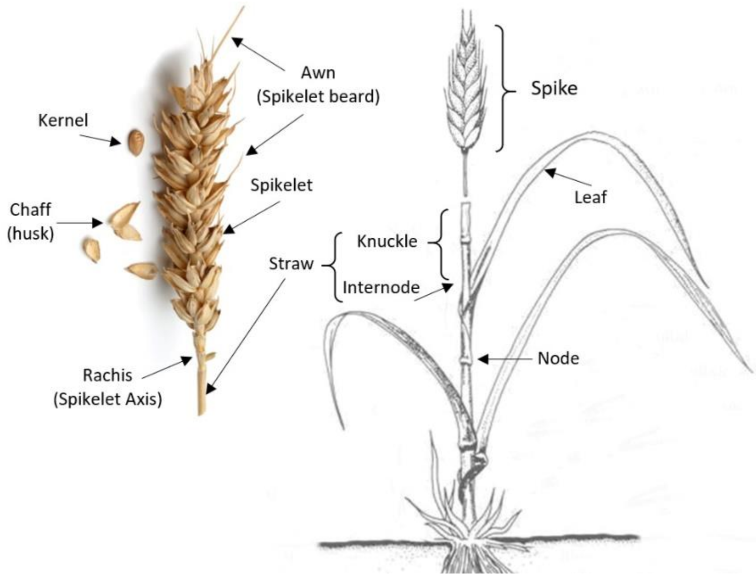

Fig. 2.1. Different parts of wheat plant which remain in bulk wheat as DFM (picture modified based on Plant morphology from The Government of British Columbia website 2020)

2.2. Segregation mechanisms

Segregation is the tendency of particles with similar physical properties to collect together in one zone during handling or loading free-flowing bulk materials (De Silva et al. 2000; Thomson 1997). This phenomenon usually occurs during heap formation when free-flowing bulk materials are filled into bags, silos and hoppers (Fan et al. 2017; Jain et al. 2013). On the contrary, the behavior of cohesive or poorly flowing bulk materials is controlled by interparticle adhesion forces, which reduce the mobility of individual particles and therefore their tendency to segregate (Schulze 2008). The process of segregation of different particles in bulk materials, particularly bulk grain, is very complicated because many factors and mechanisms are involved. Particle segregations in industrial granular materials other than grain such as soil, sand, coal and alumina during handling, loading and unloading have been studied extensively.

It is necessary to study and understand the mechanism of segregation and the factors that influence segregation in bulk materials in order to minimize or prevent segregation. Hence, mechanisms of particle segregation in bulk materials have been reviewed by several researchers and many different segregation mechanisms, including rolling, sliding, embedding, sifting, avalanche, trajectory, fluidization, impact, displacement, percolation, air current, agglomeration, push-away, and bouncing, have been identified (De Silva et al. 2000; Fan et al. 2017; Jian et al. 2019; Mosby et al. 1996; Narendran et al. 2019; Tang & Puri 2004). Usually, more than one of these mechanisms occur simultaneously, and some of these mechanisms overlap each other or may be considered a special case for another mechanism (Jian et al. 2019; Tang & Puri 2004). Besides, some mechanisms do not apply to the bulk grain, for instance, agglomeration segregation could occur only during mixing fine particles with a diameter smaller than 50 μm or in cohesive fine particles, e.g., powders due to interparticle forces (Lumay et al. 2012; Tang and Puri 2004). Segregation of particulate materials in a bulk mixture can be classified as vertical (top-to-bottom) or horizontal (side-to-side) segregation (Tang and Puri 2004). Vertical segregation means that particles with different physical properties tend to separate from each other in vertical layers due to segregation mechanisms like sifting or fluidization. On the other hand, in horizontal segregation, nonuniformity in a mixture occurs across the base of the material heap due to segregation mechanisms such as trajectory, rolling and sliding.

Some researchers have tried to classify segregation into some primary mechanisms. Johanson (1996) introduced five primary mechanisms of segregation which were trajectory, sifting, fluidization, air current, and angle of repose (Johanson 1996). Tang and Puri (2004) considered the size of the particles in a mixture as the most important factor affecting the segregation and suggested a new classification for segregation mechanisms. They proposed four primary mechanisms of segregation: trajectory (large particles), sieving (small particles), fluidization (fine particles), and agglomeration (cohesive fine particles) (Tang and Puri 2004). These mechanisms are shown in Fig. 2.2.

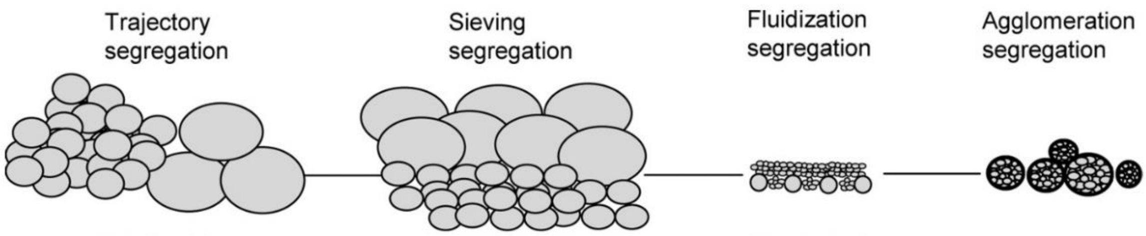

Fig. 2.2. Schematic of four primary segregation mechanisms in bulk materials suggested by Tang and Puri (2004).

Narendran et al. (2019) observed the segregation effects of rolling, sliding, impact segregation, fluidization, trajectory, and avalanches during loading wheat mixture with 3 and 6% in total of canola, kidney bean and soybean into a bin (Fig. 2.3) (Jian et al. 2019; Narendran et al. 2019; Narendran 2018). Jian et al. (2019) simplified primary patterns of segregation in grain industry to four main mechanisms that cover all segregation mechanisms that occur in bulk grain during handling and loading: trajectory, fluidization, sifting, and impact segregation. These main mechanisms are discussed in detail in this chapter. However, despite the previous studies, the mechanisms and kinematics of segregation of particulate materials are still complicated and need to be studied more.

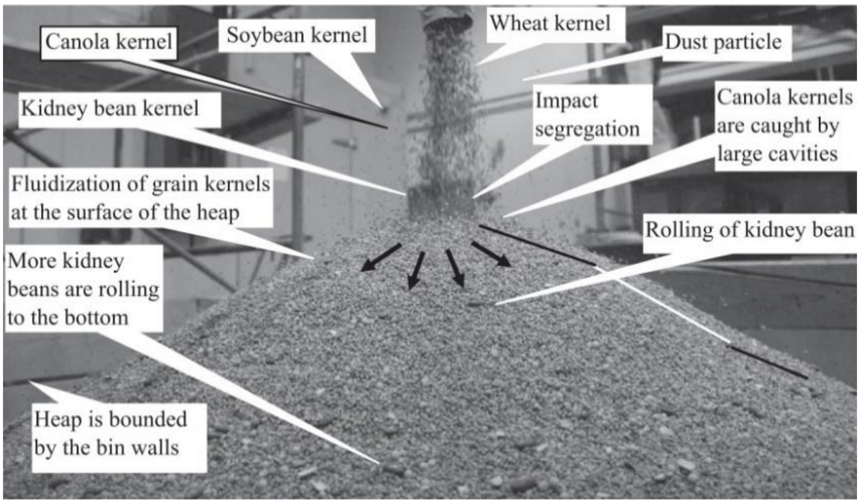

Fig. 2.3. Segregation effects observed in wheat mixture with 3 and 6% in total of canola, kidney bean and soybean into a bin (Narendran 2018).

2.2.1. Trajectory segregation

Different particles in bulk grain may have wide variations in terms of size and shape. For example, bulk wheat may contain spherical-shaped weed seeds or cylindrical-shaped straw along with oval-shaped sound wheat kernels. Particles with different sizes have different (linear) momentums when they enter a bin during loading. At a constant velocity of entering a bin, large particles have a higher momentum compared to small particles. In addition, different shapes of particles will result in different air resistances (drag force) during moving or falling. Therefore, due to difference in momentum and/or air resistance, particles with different sizes and shapes will follow different trajectories during falling or moving (Liss et al. 2004). Trajectory segregation is actually the effect of particle momentum and air friction, which changes the trajectory of moving particles. This phenomenon is called trajectory segregation that means that small particles do not travel as far as larger particles (Fig. 2.4) (Jian et al. 2019; Schulze 2008). Trajectory segregation is significant when bulk materials are loading in a horizontal or an inclined direction (such as loading a bin using an inclined chute or pneumatically conveying a solid bulk); however, it can appear when large particles are in free fall or in relatively high rolling or sliding velocity. Hence, rolling or sliding segregation are considered a special case of trajectory segregation (Tang and Puri 2004).

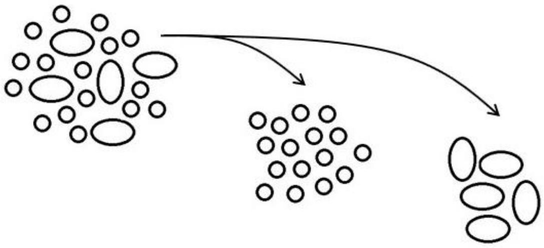

Fig. 2.4. Schematic of trajectory segregation in bulk grain.

Falling height, initial velocity and direction of loading of grain kernels during loading into a bin influence the trajectory that particles follow (Nourmohamadi-Moghadami et al. 2020). The initial direction of the grain stream plays an important role. For instance, if the grain is transported by a grain auger, the stream of grain is inclined, and the effect of trajectory on the segregation of particles will be more obvious. Small particles with less than 100 μm in diameter, like dust, will be mainly influenced by the air current. During loading grain into a bin, tiny particles such as dust tend to settle in the periphery of the bin near the wall. This is because these small particles are carried away by the air current produced by falling grains. Segregation of dust in grain with a high percentage of dust could potentially increase the risk of dust explosion (Theimer 1973). The momentum of particles larger than dust but smaller than 1-2 mm is smaller than the momentum of coarse particles. Hence, these particles will be dropped near the outlet, whereas coarse particles will be thrown far away from the center due to trajectory segregation (Chang et al. 1981). Therefore, trajectory segregation is considered a side-to-side segregation pattern. Chaff behaves like dust and is affected mostly by air currents. Jayas (1987) reported that chaff concentration was maximum close to the walls.

2.2.2. Fluidization segregation

Fluidization is a phenomenon that could occur in granular materials in the presence of fine particles or when particles are loading or unloading from height (Tang and Puri 2004). Fluidization is a top-to-bottom segregation of easily fluidized fine particles from larger particles by air current when the grain mixture is loading into a bin from the top (Tang and Puri 2004). This could happen when the particles stream loaded into a bin, drag a significant stream of air with it. In this situation, when the stream of particles touches the grain heap, the air escapes from the center towards the periphery of bin. In this situation if the air stream is sufficient, it can keep the upper layer of fine particles in a state of fluidization. Meanwhile, larger and dense particles sink through the fluidized layer (Schulze 2008).

As a result of fluidization segregation, a higher percentage of fine particles settle near the surface of the heap. If the grain bin is loaded periodically several times, then several layers with a higher concentration of fine particles may be generated and during discharging the bin, fine materials content may fluctuate. During fluidization of a layer of fine particles, the coarser particles at the top of the grain pile can flow down due to elevation potential and sink through the fluidized layer (Jian et al. 2019). This could happen owing to a difference in angle of repose of fine and large accumulated particles in the center of the grain heap. Changes in the moisture content of the particles, as well as the size and shape of the particles directly change the angle of repose and therefore affect the fluidization segregation of particles. Fluidization is considered top-to-bottom segregation. The effect of fluidization segregation is contrary to sifting segregation. While in sifting segregation, fine particles settle down under the large particles, in fluidization fine particles end up at the top of the larger particles (Fig. 2.5) (Tang and Puri 2004). Fluidization and air current segregation will result in settling fine particles on the top surface of the grain heap in the periphery of the bin (Narendran 2018). Fluidization and air current segregation could be considered as one mechanism, because both can occur concurrently in the presence of fine particles or when particles free fall from height (Tang and Puri 2004).

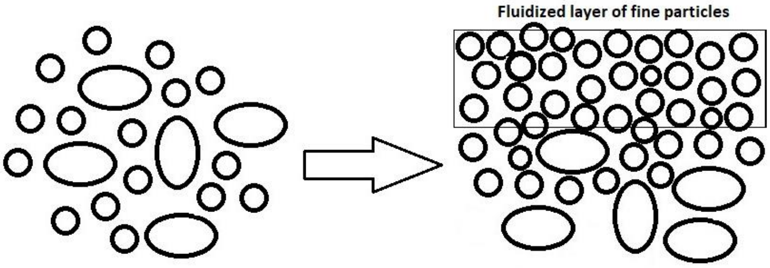

Fig. 2.5. Schematic of fluidization segregation in bulk grain.

2.2.3. Sifting segregation

When grain is loading into a bin, the grain will pile up, and a heap will form at the bottom of the bin growing gradually in height and base diameter until it is stopped by bin walls. Bulk grain is porous with a lot of intergranular spaces. During grain loading, particles in the grain mixture roll or slide down on the surface of the grain pile, and the surface acts like a sieve. This means that the smaller particles are more likely to be embedded in the surface pores and gradually percolate to the bottom of the moving layer. Therefore, larger particles have a higher probability of sliding or rolling down further from the top of the heap, while fine particles have a higher chance to be stuck and percolate at locations near the loading point (Nourmohamadi-Moghadami et al. 2020). This phenomenon is called sifting or sieving (Fig. 2.6) (Jian et al. 2019; Ketterhagen et al. 2008; Tang & Puri 2004).

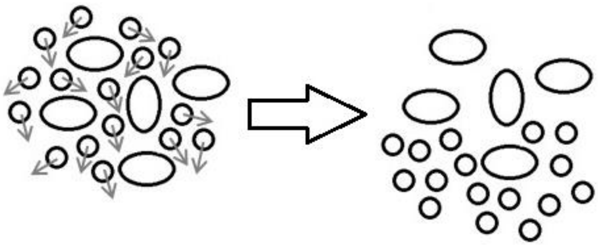

Fig. 2.6. Schematic of sifting segregation in bulk grain.

Embedding is a special case of the sifting phenomenon in grain segregation. Embedding occurs when particles falling on the top of the grain heap break the surface and penetrate the intergranular cavities (Jha et al. 2008). Embedding or percolating are the two main mechanisms of sifting segregation, therefore sometimes sifting segregation is called embedding segregation or percolating segregation. Avalanching might occur on the surface of a heap during loading bulk materials when stationary layers are formed near the center of the heap. These layers gradually become unstable with increasing the thickness of the layer and suddenly slide down the heap (Fig. 2.7). This phenomenon is called avalanching (Schulze 2008). Avalanching can intensify sifting segregation.

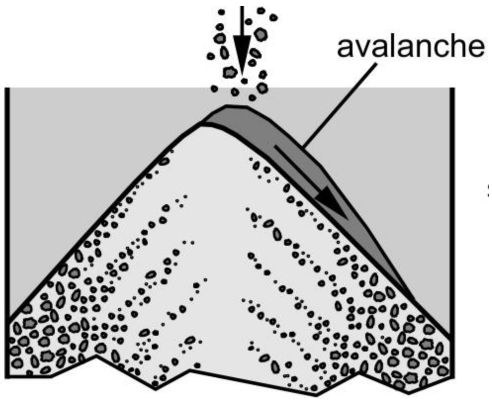

Fig. 2.7. Schematic of avalanching during heap formation (Schulze 2008).

Sifting is considered a top-to-bottom segregation mechanism (Tang and Puri 2004). However; it also lets larger particles settle further down from the top of the grain heap (Narendran 2018). In a low concentration of fine particles, the sifting mechanism of segregation becomes more significant, while fluidization is the dominant mechanism of segregation in a high concentration of fine particles (Shinohara and Golman 2002; Tang and Puri 2004). Johanson (1996) reported that a minimum size ratio of 2:1 to 3:1 is required for the sifting mechanism to occur. In another study, Johanson et al. (2005) concluded that in order to sifting segregation to occur in bulk materials, there should be a relatively large difference in particle sizes and the mixture should be free of cohesive particles that prevent free flowing of materials.

Therefore, if the bulk grain has an abnormal amount of moisture content that acts like cohesive materials, then it may not free flow, and sifting segregation may not be noticeable.

2.2.4. Impact segregation

Collision of moving particles during grain loading and unloading is inevitable. Larger particles have a higher momentum than smaller particles. Hence, when large and small particles hit together, small particles, due to lower mass and accordingly lower momentum, get a higher velocity and consequently tend to bounce further down the grain pile. This phenomenon is called impact segregation or sometimes hitting or pushing segregation (Fig. 2.8). The impact segregation acts in contrary to the sifting segregation (Jian et al. 2019). Impact segregation will result in a concentration of dense particles near the center of the grain heap, while less dense particles will be found more near the periphery of the heap. Therefore, the bulk density of the grain mixture will be higher in locations close to the grain dropping location (Narendran 2018). Narendran et al. (2019) observed the impact segregation of canola kernels in a mixture of wheat, kidney bean, soybean and canola. Impact segregation is considered a side-to-side segregation mechanism.

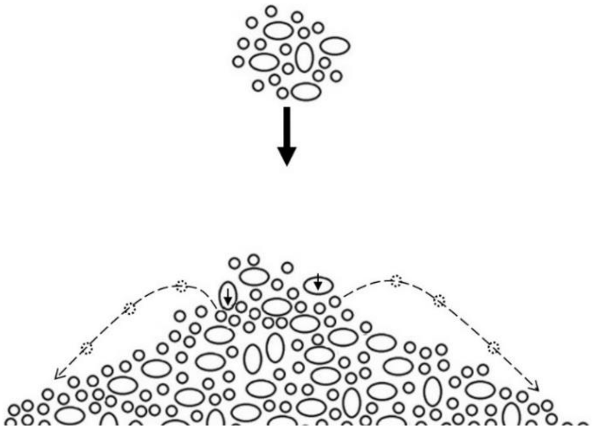

Fig. 2.8. Schematic of impact segregation in bulk grain.

2.3. Factors influencing segregation

Dockage and foreign materials may exist in bulk grain from the harvest time or can be generated when the bulk grain goes through various transportation and handling steps. For instance, when the grain is subjected to mechanical handling by elevators and augers or loaded to a bin using grain spreaders, the number of fine particles or broken kernels may increase (Dexter & D'Egidio 2012; Fiscus et al. 1971; Hall 1974; Martin & Stephens 1977). The way that bulk grain is transported from harvest field to storage bins and then to end-use buyers not only can increase the ratio of fine particles and broken kernels but also can significantly affect the distribution of DFM. Commonly, dense particles with low sphericity tend to settle in the center of the truck or railcar under the point of loading (Tang and Puri 2004). This distribution of particles in trucks or railcars will further influence the DFM distribution after the mixture is loaded into bins.

Nourmohamadi-Moghadami et al. (2020) studied the effect of broken corn and foreign material (BCFM) (that passed through a 4.8 mm diameter round-hole sieve), flow rate, falling height, and filling pipe diameter on the distribution of BCFM during loading a bin with shelled corn. A particular small bin (made by seven rings) with 1-m in diameter was constructed to enhance sampling accuracy in the radial and vertical direction (Fig. 2.9 left). Seven rings with 14 cm height were installed on a support frame on top of each other. After the bin was loaded, separator sheets were inserted between rings to divide the column of grain into eight parts. The samples were collected on a Y-shaped pattern (Fig. 2.9 right). They reported that the uniformity of BCFM distribution increased by increasing initial BCFM percentage, flow rate, and fill pipe diameter and decreasing falling height. They developed a nonlinear model to describe the distribution of BCFM.

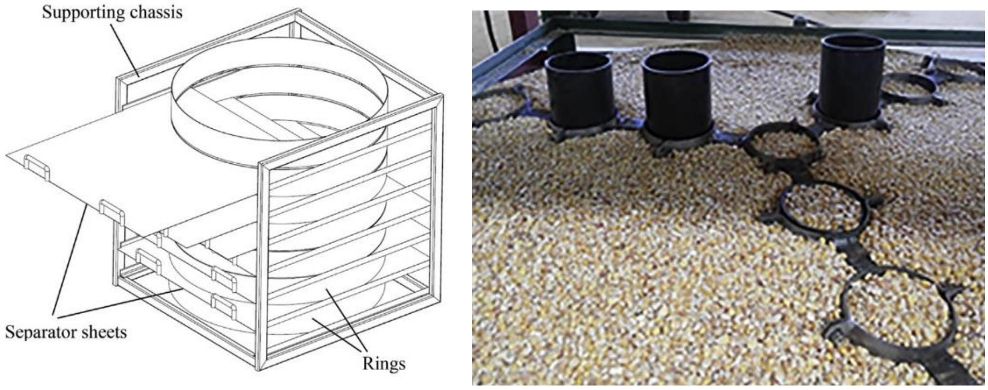

Fig. 2.9. Schematic of the used bin (left), and sampling on a Y-shaped pattern (right) (Nourmohamadi-Moghadami et al. 2020).

Factors affecting the distribution of DFM in a bin can be categorized into two groups: factors related to the handling and loading system (filling method, filling rate, filling (drop) height ,and grain bin size) and factors related to mixture properties (density, size, shape, and moisture content) and DFM properties (density, size, shape, and percentage) (Nourmohamadi-Moghadami et al. 2020; Tang & Puri 2004). The effect of size, shape, and density of DFM seems to be the most important in the segregation of particles in grain bulk (Shinohara and Golman 2002; Tang and Puri 2004).

2.3.1. Filling and discharging method

Grain can be loaded into a bin from the top with or without using a spreader or spout (Fig. 2.10). Using a spreader not only affects the number of fine materials generated but also affects the distribution of DFM. Using a special spreader (Fig. 2.11) for loading corn in a bin led to more uniformity in the distribution of fine particles and broken materials because it prevented heap formation (Nourmohamadi-Moghadami et al. 2020), whereas using a central spout increased the concentration of fine particles in the center of bin directly below the drop point of corn due to heap formation. The different methods of filling also significantly affect grain bulk density and airflow resistance of bulk grain (Stephens and Foster 1976). Chang et al. (1981) reported that the uniformity of fine particles distribution, density of bulk material, and resistance to airflow increased when corn was loaded using grain spreaders.

Fig. 2.10. Grain spreader (left) (photo from grainsystems.com), and grain spout (right)

A new Variable Filling Point (VFP) method was introduced and tested by Nourmohamadi-Moghadami et al. (2020) on a small-scale bin filled with shelled corn (Fig. 2.11). The reciprocating moving of the filling pipe, along with the rotation of the rim, produces a rose-shaped movement for the filling point over the top of the bin. Compared to the Central Filling Point (CFP), the variable filling mechanism increased the distribution of broken corn and foreign particles and eliminated the concentration of them in the center of bin. The researchers also mentioned that in the CFP method of filling, the larger filling pipe diameter results in more uniformity of particle distribution (Nourmohamadi-Moghadami et al. 2020).

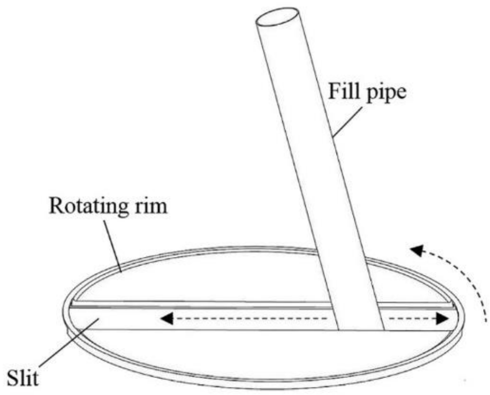

Fig. 2.11. A schematic of the variable filling point (Nourmohamadi-Moghadami et al. 2020).

For grain kernels smaller than corn like wheat, sorghum, and canola, the same result has been reported (Stephens and Foster 1978). Compared to a bin filled using a grain spout, the bulk density of sorghum and wheat were higher when a rotary grain spreader was used to load the grain into the bin (Stephens and Foster 1978). Jayas et al. (1987) observed a small increase in the uniformity of fine distribution in canola when they used a conical spreader to fill the bin. However, the concentration of fine particles in the center of bin was not significantly higher when they used a central spout. They developed quadratic equations to mathematically describe the distribution of fines and chaff in bins filled with canola.

Although discharging a grain bin, may not have a direct role in the segregation of unloaded materials, but if the grain loaded in the bin has segregated during loading, then the unloading system becomes important. In hopper bottom bins, depended on the design of the bin, mass flow, or funnel flow of materials during discharging may happen (Ketterhagen et al. 2009). Mas flow has a first-in, first-out flow pattern while funnel flow happens in a first-in, last out pattern (Fig. 2.12) (Tang and Puri 2004). Funnel flow discharging intensifies the segregation of materials because it allows the core of the bin (which probably has a higher concentration of fine or dense particles) to discharge first. On contrary, during mas flow discharging of a bin with a side-to-side segregation pattern, particles will remix and nonuniformity will decrease (Mosby et al. 1996; Tang and Puri 2004).

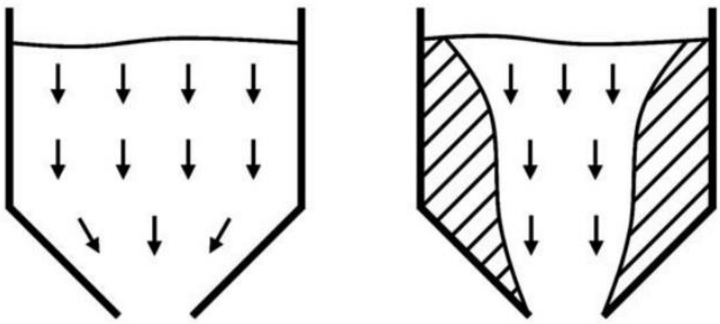

Fig. 2.12. A schematic of mass flow (left) and funnel flow (right) in a hopper bottom bin (Tuzun and Nedderman 1982).

2.3.2. Filling rate

Filling rate can influence the initial velocity of particles in grain mixture when they enter the bin. The initial velocity of particles may affect the trajectory that particles follow or may increase the air entrainment in falling particle stream, and therefore may influence the distribution of particles. Generally, the uniformity of particles in a mixture increases with increasing filling rate (Shinohara 1997; Tang and Puri 2004). Using a flow control device, for example, an orifice to control the filling rate of grain in a bin (choke-flow method), decreases relatively the velocity of particles entering the bin. Subsequently, the segregation of different particles in grain mixture during falling may reduce. The uniformity of fine particle distribution increased for corn transferred by a choke-flow system compared to the spout filling (Chang et al. 1986). However, the distribution of particles in wheat and sorghum was not influenced by using a choke-flow device (Chang et al. 1983). Shinohara and Mlyata (1984) reported that increasing filling rate decreased segregation. One reported reason for this is that in a low flow rate filling, the downward flowing layer of particles on the top surface of the grain pile becomes thicker and gives a higher chance to small particles to move further down before they percolate to lower layers (Nourmohamadi-Moghadami et al. 2020). In contrary to this, it was reported that a low filling rate increased the segregation of multi-sized particles in grain mixture loaded into a two-dimensional hopper (Shinohara and Golman 2002).

2.3.3. Filling (Drop) height

Farm grain bins are usually filled from the top of the bin. This means that grains are to be dropped from height to the bottom of the bin. Generally, loading grain from a height gives more chance to particles in the grain mixture to collide together during falling and gives them a higher momentum. Therefore, the trajectory that particles follow will get more affected by other particles, and impact segregation and fluidization will get intensified (Jian et al. 2019).

Intensifying impact segregation could result in decreasing side-to-side segregation and more uniformity of fine particles between the center and periphery of the bin. However, intensifying fluidization could result in increasing top-to-bottom segregation and accumulating of fine particles at the top layers of the mixture heap. Increasing the falling height of the mixture resulted in increasing the uniformity of broken corn kernels between the center and outer wall of the bin (Nourmohamadi-Moghadami et al. 2020). For fine particles larger than 250 μm, side-to-side uniformity increased with increasing free-fall height (Drahun and Bridgwater 1983) while fine particles less than 250 μm were not usually affected by drop height (Mosby et al. 1996).

Furthermore, by increasing drop height the final velocity of particles at the moment of hitting the top of the grain heap will increase, and consequently, some other segregation mechanisms such as impact segregation will get intensified. During filling the grain mixture from a higher free fall point, coarse particles will obtain a higher momentum at the moment of hitting the top of the grain heap and will tend to penetrate to the surface of the heap. In contradiction, fine particles will bounce off from the top of the heap to locations further from the loading point (Tang and Puri 2004).

Narendran et al. (2019) investigated the effect of three different loading heights (0.8, 1.6 and 2.4 m) on the segregation of canola, kidney beans and soybeans mixed with wheat. They reported that regardless of the percentage of other grains, the loading height significantly influenced the distribution of canola but had no significant effect on the distribution of soybeans and kidney beans in the wheat mixture. The effect of three loading heights (0.65, 1.30 and 1.95 m) on the distribution of canola (4.5% by mass) and soybean (4.5%) mixed with wheat in a square bin filled by a central spout was studied (Parker et al. 2005). The authors reported that drop height significantly affected the distribution of both components larger and smaller than wheat (Parker et al. 2005). Nourmohamadi-Moghadami et al. (2020) found that as the heap of grain raised in a 1-m diameter bin filled by shelled corn mixed with broken kernels and foreign materials (BCFM), the amount of BCFM found in the periphery of the bin decreased. They explained this by the fact that at lower falling height (when the grain level increases in the silo), the velocity of the particles in the flowing layer of the grain on the heap surface decreases and therefore gives more time to the small particles to prelocate between large particles. Therefore, during loading a bin, specially commercial-scale bins with a considerable height, the maximum uniformity of fine particles occurs at the bottom of the bin and the maximum segregation occurs near the top of the grain level (Nourmohamadi-Moghadami et al. 2020). In contrary to these studies, Chang et al. (1986) pointed out that regardless of the method of filling, loading height had no significant effect on the distribution of fine particles in bulk corn (Chang et al. 1986). Jayas (1987) also reported that the effect of drop height (maximum 7 m) on the distribution of fines and chaff in canola was insignificant.

2.3.4. Size and geometry of bin

Most of the studies on DFM distribution inside grain mixture have been done on relatively small bins compared to bins usually used by farmers. Heap formation during loading grain into a bin is one of the main reasons that trigger particle segregation. Increasing the diameter of bins increases the base of the grain heap formed during loading. A bigger width of the pile gives more chance to the particles at the surface of the heap to move a longer distance. This will intensify some mechanisms of segregation, such as sifting, and will result in more segregation (Mosby et al. 1996). Besides, as discussed in the previous section, by increasing the height of bins, the drop height of particles during loading increases and could result in intensifying impact segregation or fluidization of fine particles. There are not many studies on the effect of bin size or shape on the segregation of grain mixture. Prasad (1974) reported that the distribution of dockage smaller and larger than wheat kernels in bulk wheat followed the same trend in 4.2 m and 5.4 m diameter bins. Ketterhagen et al. (2008) simulated segregation of particulate materials during unloading of a quasi-three-dimensional hopper using discrete element method. They reported that segregation was significantly influenced by the hopper geometry and by making the walls of the hopper steeper, segregation decreased.

2.3.5. Size, shape, and density of grain kernels and DFM

Different grains have different physical properties in terms of size, density, shape, sphericity, angle of repose, roughness (surface properties), aerodynamic properties, brittleness, ability to absorb moisture and cohesiveness (Schulze 2008; Tang and Puri 2004; Thomson 1997). For instance, compared to kidney beans, canola kernels are tiny with higher sphericity. Besides, the type and size of DFM vary among the different grain. Previous studies have shown that the grain type affects the distribution of DFM in grain mixture. It has been reported that difference in particle size is the most important reason for segregation in bulk materials (Thomson 1997).

For bulk materials, segregation increases when the size ratio of particles increases (Johanson 1996; Tang & Puri 2004). Stephens and Foster (1978) pointed out that the segregation of fine particles in wheat and sorghum was lower than the segregation of them in corn. They indicated that this was due to the difference in size between corn kernels and wheat and sorghum kernels. Corn kernels are bigger than wheat and sorghum kernels and have larger spaces between whole kernels. This fact increases sifting segregation in bulk corn. However, another study by Chang et al. (1983) showed no difference in the trend of fines distribution between corn, wheat and sorghum loaded into 6.4 m diameter bins.

Johanson (1996) reported that a minimum size ratio of 2:1 to 3:1 is required for the sifting mechanism of segregation to begin. Chang et al. (1986) reported that in both choke-flow and spout-flow filling methods, the concentration of particles smaller than 4.76 mm diameter in corn (with a rough diameter of 5 mm), was higher in locations near the center of bin. The effect of particle size on segregation of grain mixture filled into a square bin was studied in bulk wheat mixed with 4.5% canola and 4.5% soybean as dockage representatives. Particles smaller than wheat kernels accumulated more in the center of bin, and coarse particles larger than wheat kernels were more found close to the walls (Parker et al. 2005). In bulk wheat mixed with canola, soybean and kidney bean loaded into a 2 m diameter bin, larger grain than wheat kernels (kidney beans and soybeans) accumulated mostly far from the walls in the mid locations and center of the bean. In contrast, canola kernels, which are smaller than wheat kernels, were found more near the walls (Narendran et al. 2019). There was no significant difference in the concentration of fine particles in the canola mixture in the center of bin compared to the periphery (Jayas et al. 1987). The amount of dockage either smaller or larger than wheat kernels was not significantly different among the radii of the bin filled with wheat. The same results were observed for the distribution of dockage smaller than rapeseed in bulk rapeseed, but contrary results were reported for dockage larger than rapeseed kernels. The amount of total dockage and the amount of dockage component bigger than rapeseed kernels were significantly higher in the periphery of the bins filled with bulk rapeseed (Prasad 1974; Prasad et al. 1978).

The density of grain particles and DFM is another important factor that affects the segregation. During vertical loading of grain, dense particles usually settle under the loading point near the center of bin and do not tend to follow long trajectories (Shinohara and Golman 2002; Tang and Puri 2004). In a vibration container of bulk materials, for instance, during transporting the grain, the dense particles tend to sink to the bottom of the mixture (Venables and Wells 2001).

Segregation phenomenon is easier to occur in a bulk grain mixed with DFM with different particle shapes than a mixture with similarly shaped particles (Shinohara & Golman 2002; Tang & Puri 2004; Johanson 1996). Tang et al. (2003) reported that in a mixture of irregular shaped coarse particles with spherical shaped fine particles, segregation is higher compared to a mixture of spherical shaped coarse and spherical shaped fine particles (Tang et al. 2003). However, the effect of the size ratio of particles in grain mixture is more significant than the effect of shape (Swaminathan and Kildsig 2002). Shape of particles affects their aerodynamic properties. Aerodynamic properties are used in the handling of grain. Drag coefficient and terminal velocity are two of the most important aerodynamic properties which are used in pneumatic transportation, separation of DFM from grain and cleaning the grain (Gorial and O'Callaghan 1990; Song and Litchfield 1991). These parameters can be influenced by the size, shape and sphericity of grain and other particles (West 1972) and can influence trajectory or fluidization segregation (air current segregation). The drag force applied to a grain kernel moving or falling in the air is calculated from Equation 2.1 (Mohsenin 1986).

$$F_D = \frac{1}{2} C_D \rho_A A_f V_r^2 \tag{2.1}$$

Where;

F_D is drag force (N),

C_D is drag coefficient,

ρ_A is air density (kg/m^3),

A_f is frontal area (m^2)

and V_r is the relative velocity of air with grain kernel (terminal velocity) (m/s).

Zewdu (2007) reported that node free straws of the teff plant had lower terminal velocities compared to straw with nodes. He also observed that by increasing the moisture content of the grain, the terminal velocity of grain increased. Uhl & Lamp (1966) reported that the terminal velocity of grain kernels (wheat, rye and oat) is higher than its related chaff and straw.

2.3.6. Angle of repose

The angle of repose or repose angle (slope angle or cone angle) is one of the bulk material characteristics that is influenced by size distribution and shape of particles and has a major effect on particle segregation in a mixture. Other particle properties such as particle roughness and cohesiveness can also affect the angle of repose. So, it is important to study the angle of repose of mixture separate from particle properties. The angle of repose is defined as the slope of the stationary formed pile concerning the horizontal base of the pile (Mohsenin 1986). There are two types of the angle of repose in bulk grain: emptying angle of repose when the grain is unloaded from the bottom of a bin and filling angle of repose when grain pile is forming during loading bulk grain (Mohsenin 1986). Fig. 2.13 shows a simulation of the filling angle of repose of granular materials (Mazhar et al. 2014). It has been reported that the emptying angle of repose is 3° to 10° bigger than the filling angle of repose (Bhadra et al. 2017).

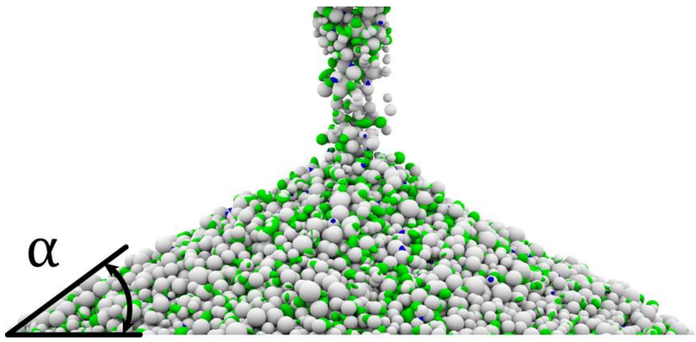

Fig. 2.13. The filling angle of repose simulation (Mazhar et al. 2014).

Angle of repose is a key parameter in designing grain bins and determining flow characteristics of bulk grain (Bhadra et al. 2009; Zhou et al. 2008) and powders (Santos et al. 2018). It plays an important role in the segregation of particulate materials so that sometimes it is considered a separate segregation mechanism. The reported angle of repose in the most of previous studies is usually from laboratory measurements. Measuring angle of repose under field conditions considers the effect of compaction caused by different drop heights and can be different from what is measured in laboratory. Angle of repose that is measured in real situation in farm bins and considers the effect of compaction caused by drop height is called in-situ angle of repose or in-bin angle of repose. Bhadra et al. (2017) measured the in-situ filling angle of repose of several crops, including hard red winter wheat in field conditions. They reported an angle of repose with a median value of 22.2° for wheat. It is widely reported that the angle of repose is significantly influenced by the particle size distribution (Samadani and Kudrolli 2001; Santos et al. 2018), and for cohesive materials, it is hard to measure (Al-Hashemi & Al-Amoudi 2018). Recently, optical methods and photographic analysis have been used to measure the angle of repose more accurately than traditional methods (Bhadra et al. 2009; Kurkuri et al. 2012). Jian et al. (2019) summarized the filling and emptying angle of repose of common crops and reported that for most grain, the angle of repose is in the range of 24 - 44°, however they did not mention that whether the reported angles of repose were measured in-situ or in laboratory.

When a mixture of grain particles of different sizes including high percentage of fine particles is loaded into a bin, fine particles at the top of the grain heap may be at the state of fluidization. In this situation, if there is a difference between the angle of repose of small particles and large particles, the particles at the top may flow down the heap because of the smaller angle of repose (Jian et al. 2019). Therefore, when the angle of repose of particles rested at the top of the heap in more than other particles, the heap will be steeper in the upper part (Fig. 2.14), and these particles will be more stable at the top of the heap (Schulze 2008). Consequently, fluidization segregation decreases (Liao 2018), and particles with a lower angle of repose will be found in the periphery of the heap. Increasing the percentage of dockage from 5% to 15%, significantly increased the angle of repose of hemp seeds (Jian et al. 2018). Also, the angle of repose of corn stover particles increased by increasing the particle size (Zhou et al. 2008). The presence of insects could increase the percentage of dust in grain and subsequently, the presence of dust could increase the angle of repose because dust increases the contact area between particles (Bian et al. 2015). The insect-infested wheat had a higher angle of repose compare to non-infested wheat (Bian et al. 2015).

The presence of a small amount of liquid can have a significant effect on the angle of repose of bulk materials. Due to cohesive forces introduced by the presence of a liquid, the angle of repose of a pile of wet granulate materials is higher than a dry pile of the same material (Samadani and Kudrolli 2001). Similarly, the angle of repose of grain is connected to the moisture content of grain, and increasing the moisture content could result in increasing the angle of repose (Bhople et al. 2017; Bian et al. 2015; Karimi et al. 2009; Tabatabaeefar 2003) and decreasing fluidization of fine particles and dust. Bhople et al. (2017), reported that the angle of repose of paddy, maize, soybean, and pea increased as the moisture of content increased. The angle of repose increased for five varieties of wheat when moisture content increased from 0 to 22% (dry basis) (Tabatabaeefar 2003). Also, for three other varieties of wheat, angle of repose linearly increased in the range of 23 - 27° by increasing the moisture content from 9.5% to 12.5% (w.b.) (Zaalouk and Zabady 2009). The angle of repose increased for two varieties of hard red winter wheat, with increasing moisture content from 11.67% to 13.35% (w.b.) (Bian et al. 2015) and for hemp seeds the emptying angle of repose increased by increasing moisture content from 9% to 15 % (w.b.) (Jian et al. 2018).

The main reasons for differences in the angle of repose of non-cohesive particulate materials are the shapes and sizes of the particles. Irregular-shaped and sharp-edged particles have a higher angle of repose compared to rounded particles (Fu et al. 2020). Therefore, if these two groups of particles mix well and are loaded into a bin, un-rounded particles form a steeper heap in the center and rounded particles roll on the heap downward (Fig. 2.14 left). Besides, generally, fine particles due to stronger adhesive forces can form a steeper heap compared to larger particles (Fig. 2.14 right) (Schulze 2008; Shimoska et al. 2013; Teferra 2019). Liao

(2018) reported that segregation declined when emptying angles of repose of particles increased.

Drop height of particles is another factor that has been reported to affect the filling angle of repose of particulate materials. However, there are few studies on the effect of drop height on the filling angle of repose of bulk materials and no study was found on the effect of drop height on the filling angle of repose of bulk grains, particularly for wheat. The results of a controlled experimental study showed that the angle of repose of loose materials in geomorphic investigation varies directly with their moisture content, roughness, and angularity but inversely with the drop height of particles (Van Burkalow 1945).

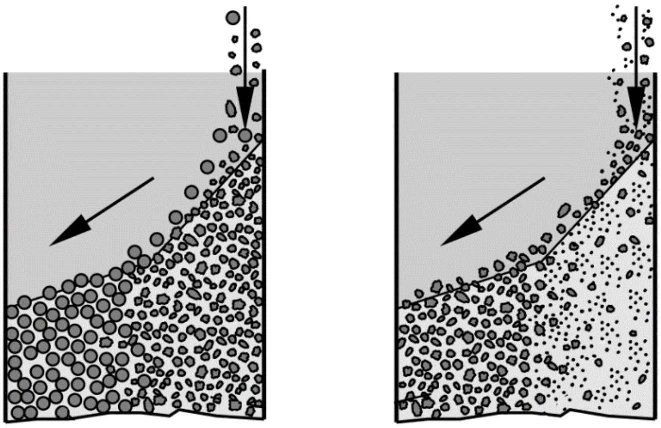

Fig. 2.14. Schematic of segregation in non-cohesive bulk materials due to different angles of repose resulting from particle shape (left) and size (right) (Schulze 2008).

2.3.7. Percentage of DFM

Several studies have investigated the effect of DFM size on segregation occurred in grain mixture during grain loading into bins. However, there are only few studies on the effect of the percentage of DFM on segregation in grain mixture. In a low concentration of fine particles, the sifting mechanism of segregation becomes more significant, while fluidization is the dominant mechanism of segregation in a high concentration of fine particles (Shinohara and Golman 2002; Tang and Puri 2004). As discussed in the previous section, different percentages of DFM in grain mixture can influence the angle of repose of bulk grain (Jian et al. 2018), which is a critical flowability indicator of bulk grain. The angle of repose of hemp seeds increased with increasing the percentage of dockage from 5% to 10% and then to 15% (Jian et al. 2018). By increasing the chaff proportion in bulk wheat, the flowability of bulk wheat decreased (Bian et al. 2015). Changes in the flowability of bulk grain may influence segregation mechanisms taking place in grain during handling and loading. For cohesive powders, the flowability is low, and therefore the scale of segregation is small (Harnby 2000).

The percentage of kidney bean, soybean and canola (0, 3 and 6% in the total mixture) in wheat, did not significantly influence the segregation of grain mixture loaded into a 2-m diameter test bin (Narendran 2018). Increasing the number of small components in grain mixture loaded into a two-dimensional hopper, increased the segregation of particles (Shinohara and Golman 2002). By increasing the percentage of broken corn and foreign materials (BCFM) mixed with shelled corn, the uniformity increased. The researchers concluded that this could be due to the fact that grain containing a higher percentage of fine particles can form a steeper heap. A steeper heap will result in increasing the velocity of the flowing layer on the top of the heap and lets the fine particles to reach the locations further from the loading point (Nourmohamadi-Moghadami et al. 2020).

2.3.8. Moisture content of the mixture

Moisture content is a critical parameter in the storage of grains. In long term storage of grains in bins, due to free convection currents between intergranular spaces inside the bin or due to forced air movement during aeration and drying, moisture can translocate from one part to another part of the bin (Brooker et al. 1992; Hall 1980; Hammami et al. 2016; Smith & Sokhansanj 1990). It has been proven that cohesive forces due to liquid bridges formed in the presence of a liquid in bulk materials, increases the angle of repose (Samadani and Kudrolli

2001). The angle of repose of wheat, maize, soybean, pea, and hemp seed increased by increasing moisture content (Bhople et al. 2017; Jian et al. 2018; Tabatabaeefar 2003). Higher moisture content increased the angle of repose of bulk grain and dynamic coefficient of friction of grain kernels (Kalkan and Kara 2011). These are two indicators of grain flowability (Bian et al. 2015). Therefore, moisture content can directly influence the flowability of bulk grain and, subsequently, the segregation mechanisms in bulk grain during handling and loading. The flowability of bulk wheat is reduced by increasing moisture content (Bian et al. 2015). Bagster (1996) reported that by increasing moisture content, segregation decreased in sand particles.

Moisture content also can affect the size and morphology of grain kernels (Tahir et al. 2007). When a grain kernel absorbs enough water, it may swell and become larger (Al-Mahasneh and Rababah 2007). As already discussed, changes in the size of particles can directly affect the angle of repose of particles, and also the segregation of them in the bulk state (Schulze 2008; Shimoska et al. 2013). Moreover, environment temperature might also affect the dimensions of grain kernels and consequently the segregation behavior of bulk grain. This fact could be considerable in countries such as Canada where temperature variation is high during one year. However, no study was found on the effect of bulk grain temperature on particle segregation.

2.4. Minimize segregation

Understanding the mechanisms of segregation in bulk materials as well as the factors that trigger and affect segregation patterns, could help to minimize or prevent segregation. In other words, minimizing segregation depends on minimizing or eliminating the cause of segregation (Johanson et al. 2005). Generally, methods to minimize segregation in bulk materials can be classified into two types: firstly, modification of bulk materials properties, and secondly proper design of bulk material storage and transporting machinery and optimization of material handling processes (Jian et al. 2019; Tang & Puri 2004).

Modifying bulk material properties in terms of size, shape, and density can generally lead to minimizing all segregation patterns (Tang and Puri 2004). Mosby et al. (1996) suggested that the most effective way to prevent segregation in a material mixture is to reduce the size distribution of particles. However, this approach is not always applicable and may be expensive. Carson et al. (1986) reported that when the size ratio of particles is less than 1.3:1, size segregation can be minimized. Venables & Wells (2001) suggested that in powders, reshaping particles with irregular shapes by methods such as granulation, milling, or recrystallization as well as reducing the particle size distribution, could result in less size segregation and agglomeration. Besides, if the size and shape of particles in grain mixture are relatively similar, then the difference between the angle of repose of particles could decrease and the segregation associated with that may be limited (Liao 2018). Tang & Puri (2004) reported that by decreasing the size ratio of particles in the mixture, segregation decreased. This could happen due to the reduction in sifting and percolation segregation especially in low concentration of fine particles when the sifting mechanism of segregation becomes more significant (Shinohara and Golman 2002). The effect of increasing moisture content of particles on reducing the flowability of bulk materials can be used to decrease segregation in powders (Mosby et al. 1996) or dust level in grains (Jayas et al. 1992); however, adding too much water or oil could result in increasing cohesiveness of particles and other problems (Carson et al. 1986). Moreover, adding moisture method does not apply to bulk grain because the grain needs to be stored at a safe moisture content.

Designing and selection of grain bins and related machinery should be considered in a way to reduce large heap formation. The best way to minimize sifting segregation mechanisms is to reduce the heap size (Mosby et al. 1996; Shinohara 1997). The heap size of grain mixture increases with bin size. Therefore, in relatively large bins, side-to-side segregation mechanisms could increase due to large heap formation (Tang and Puri 2004). In other words, by reducing the diameter of the grain bin and preventing large heap formation, segregation may be limited. Mosby et al. (1996) and Shinohara (1997) reported that reducing free-fall height during loading the grain into large bins could decrease fluidization segregation. Having said that, due to the surge in grain production in recent decades, using large grain bins is necessary and more economical. Segregation mechanisms associated with a difference in the angle of repose of particles in grain mixture can be minimized by limiting heap formation especially in a high concentration of fine particles (Shinohara and Golman 2002; Tang and Puri 2004).

Using proper methods of filling such as a grain spreader (Chang et al. 1986) or a variable filling point (Nourmohamadi-Moghadami et al. 2020) instead of a central spout reduced heap formation and resulted in more uniformity of particles distribution. Using this type of distributers, bulk materials during loading will form several small heaps or flat layers instead of a large heap in the center of bin (Thomson 1997). Other methods such as using an egg-box insert or cylinder-in-cylinder insert to divide the bin into small sections have been suggested to reduce heap size formation during filling. Also, using an inclined chute to reduce free-fall height and control air current during loading a bin by very fine materials such as powders could help to minimize fluidization (Tang and Puri 2004). It has been reported that changes in the filling rate of grain had contrary effects on particle distribution (Chang et al. 1986; Shinohara and Mlyata 1984). Jian et al. (2019) reported that segregation can be reduced by using the maximum capacity of the transporting device's feeding rate. Therefore, depending on the nature of the grain, changing the filling rate of grain during loading into the bin may decrease the segregation mechanisms.

Proper design of the hopper bottom grain bin can also result in more uniformity of bulk grain. It is suggested that in hopper bottom bins, by making the walls of the hopper steeper, segregation decreases during discharging (Ketterhagen et al. 2008). However, this approach will make the bin taller. Bulk materials will remix and uniformity will increase, if the hopper bottom bins are designed in a way that allows the bulk materials discharge in a mass flow pattern instead of a funnel flow pattern (Mosby et al. 1996; Tang and Puri 2004). Thomson (1997) recommended that multiple discharging pipes can be used to discharge materials from different locations of a bin and remix them at the outlet point (Thomson 1997). Segregation in a screw or en-masse conveyors is usually negligible because these conveyors usually work at low speeds (McGlinchey 1998). The vibration of handling and processing machinery such as transporting conveyors and augers could result in the segregation of particulate materials. Vibration makes larger particles to move upward through a mass of smaller particles (Williams and Shields 1967). Eliminating the vibration of machinery by proper maintenance could result in segregation reduction (Shinohara 1997). However, vibration may be applied intentionally to help the movement of a powder or to consolidate a powder into a mold (Harwood 1977). Agglomeration segregation usually occurs during mixing powders due to interparticle forces such as surface tension or electrostatic. Using a high speed impeller in mixing chamber could prevent agglomeration (Tang and Puri 2004). Remixing materials during discharging from bins and containers (that may have been already segregated during loading) is another approach to minimize the detrimental effects of segregation (Schulze 2008). In addition, several procedures, including pre-cleaning, leveling during loading intervals, and coring after loading have been proposed to enhance the uniformity of grain mixture in a bin (Nourmohamadi-Moghadami et al. 2020). Optimization of grain handling processes, for example, decreasing the turning time of stored grain can reduce the generation of more broken kernels or fine particles and consequently decrease non-uniformity of the mixture (Jian et al. 2019).

2.5. Detrimental effects of segregation in bulk grain

Segregation of different particles in bulk grains, chemicals, and pharmaceutical materials is a huge problem for storage, quality control, and handling. In the grain industry, segregation of particles in bulk grain mixtures during handling, loading, and unloading is unavoidable. This segregation results in uneven distribution of DFM in grain mixture and consequently will change some physical properties of bulk grain such as porosity, bulk density, and airflow resistance. These changed properties may influence the quality of the grain or final products (Fig. 2.15).

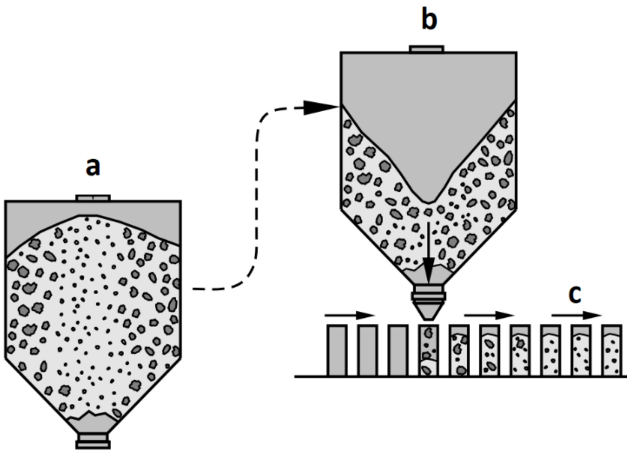

Fig. 2.15. An example of the detrimental effect of segregation on final products (Schulze 2008). a) Segregation of particles in a container during loading. b) Funnel flow of segregated particles during discharging. c) Uneven distribution of particles in final products.

2.5.1. Porosity and bulk density (test weight)

Bulk density (test weight) is widely accepted as an indicator of milling potential by milling industry and is considered a grading factor in wheat trading (Wang & Fu 2020). Bulk density of grain is influenced by moisture content and true density of kernels (Dexter and D'Egidio 2012). Dockage and foreign materials in bulk grain usually have different physical properties such as bulk and true density and porosity compared to desired grain kernels. This means that the accumulation of DFM in some parts of the bin can result in changing porosity and bulk density of the grain mixture. If samples are collected from different locations of a bin and then bulk density of samples are measured in laboratory, any differences that are observed between bulk densities of collected samples are due to the differences in the percentage of segregated particles not due to compaction caused by drop height. Effect of compaction on bulk density due to drop height can be determined by measuring in-situ bulk density which means that measuring bulk density in bin without disturbing bulk grain. In-situ bulk density is different from test weight because test weight is measured in laboratory using test weight apparatus. Porosity and bulk density have an inverse relationship (Koc et al. 2008), i.e., by increasing porosity bulk density decreases and vice versa.

Narendran et al. (2019) studied the effect of segregation of a mixture of wheat with kidney bean, soybean and canola (referred to as other grains) on bulk density. Since all three of these other grains have a lower bulk density than wheat (Jayas & Cenkowski 2010), they reported that in locations with high accumulation of other grains, bulk density of grain mixture decreased. However, the percentage of other grains did not have a significant effect on the trend of bulk density distribution. Since the density of chaff was significantly lower than wheat kernels, bulk density of wheat mixture in all three different moisture content levels (10%, 12%, 14% w.b.) reduced by increasing the percentage of chaff in bulk wheat from 0 to 7.5% on a weight basis (Bian et al. 2015). The bulk density and porosity of wheat at 12.7% moisture content (w.b.) grown in west Canada were reported in the range of 763 – 780 kg/m^3 and 38 - 39% for hard red spring wheat, and 744 – 794 kg/m^3 and 38 – 41% for durum wheat, respectively (Muir and Sinha 1988). Jayas et al. (1989) developed empirical linear equations for porosity and bulk density of canola as functions of chaff and fines. They studied the effect of chaff and fines on porosity and bulk density of two varieties of canola in a range of 0 - 25% of chaff and fines by mass. Although the percentage of chaff compared to fines had a more significant influence, by increasing the percentage of either chaff or fines, the porosity of canola mixture linearly increased, and bulk density linearly decreased.

2.5.2. Airflow resistance

Temperature and moisture content are two critical parameters in stored grain because they affect insect multiplication and fungi growth and, subsequently, the spoilage of grain (Jayas et al. 1994; Noyes et al. 2002; Olatunde et al. 2016). Moisture content of harvested grains is usually higher than required for processing or safe storage. This excess moisture can be removed by forcing air with the proper temperature and relative humidity through bulk grain during storage in bins. Hence, drying to remove moisture and aeration to remove heat are critical unit operations during storing grain in bins (Moses et al. 2013).

The study of airflow resistance through bulk grain is an essential consideration in the design and application of drying and aeration systems in grain bins (Shahbazi 2011). Resistance to the airflow develops due to energy lost through friction and turbulence when air is passing through bulk grain (Gornicki and Kaleta 2015a). Several theoretical and empirical models have been reported for estimating air pressure drop in bulk grain. These models have been used by researchers to study the effect of the presence and distribution of DFM in bulk grain on airflow resistance of bulk grain. Among all, predictive models reported by Ergun (1952), Shedd (1953) and Hukill and Ives (1955) have been used and modified by many researchers. Ergun developed a model of the Equation 2.2 form (Gornicki & Kaleta 2015a). Several modified equations have been derived from Ergun's model.

$$\Delta P = 150\frac{v\mu}{d_e^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} + 1.75\frac{\rho v^2}{d_e}\frac{(1-\varepsilon)}{\varepsilon^3} \qquad (2.2)$$

Where;

ΔP is the pressure drop per unit height (Pa/m),

V is airflow rate per unit area (superficial velocity) ($m^3/s.m^2$),

d_e is equivalent particle diameter (m), ε is porosity,

μ is dynamic viscosity of air (Pa.s),

and ρ is density of air (kg/m^3).

One of the most critical factors that affect the airflow resistance in the bulk grain is the presence of DFM because fines, dust and small particles in DFM can fill pore spaces between grain kernels and hinder or prevent air movement (Olatunde et al. 2016). As it is clear in Ergun's model (Equation 2.2), the air pressure drop in a column of bulk grain is inversely proportional to the cube of the porosity of bulk grain. This means that by decreasing porosity, airflow resistance in a column of grain increases. Segregation in bulk grain during loading into a bin makes the bulk grain non-uniform. Generally, small and dense particles accumulate in the center of bin and settle in spaces between coarser particles, and therefore decrease the porosity of bulk grain in the center of bin. By decreasing porosity, based on Ergun's equation, airflow resistance increases. This phenomenon will disturb natural air circulation in bins and in case of drying or aeration, more power will be needed to blow air through bulk grain (Hagstrum et al. 2012). Over drying at high air velocity locations in grain bin and grain with higher moisture content at the low airflow locations in the same bin are the detrimental effects of increasing airflow resistance due to uneven distribution of DFM in a grain bin (Nourmohamadi-Moghadami et al. 2020). Furthermore, fumigation in grain bins with uneven distribution of DFM will have low efficiency (Harein 1961).

Generally, bulk grain mixed with a higher percentage of small particles offers more resistance to airflow than cleaned grain (Gornicki and Kaleta 2015b; Hagstrum et al. 2012; Yang et al. 1990) because these fine particles fill the void spaces between grain kernels. The airflow resistance of bulk corn increased with an increase in fine particles smaller than 4.76 mm (Haque et al. 1978). Fine particles removed by either screening or aspiration from bulk corn reduced airflow resistance significantly (Yang et al. 1990). Similarly, Grama et al. (1984) reported that with an increase in the amount of fine particles in shelled corn and with a decrease in size of fine particles, airflow resistance increased. Pressure drop in clean bulk wheat was lower than unclean wheat (Kumar and Muir 1986). In oat seeds, the presence of foreign materials had the same expected effect and increased the airflow resistance (Pagano et al. 2000). In another study, the increase of fine particles increased the airflow resistance of bulk flax seeds, while the increase of chaff had an inverse effect and decreased the airflow resistance (Pagano et al. 1998).

2.5.3. Insects multiplication and fungi growth

Some previous studies have shown that the percentage of DFM in stored grain can significantly affect the multiplication of insects, and the risk of insect infestation in grain with a higher percentage of DFM is more than in clean grain (Arbogast et al. 1998; Hagstrum et al. 2012; Jian et al. 2005). Insect were found to be more active in the center of bin where the concentration of fine materials was higher (Adam et al. 1994). Wheat with more than 31 insect-damaged kernels in 0.1 kg is considered insect-infested (United States Department of Agriculture 2016). The presence of DFM and broken kernels provide accessible oviposition sites for grain insect pests to lay eggs (Jian et al. 2005). Moreover, DFM has often more moisture content and provides a good source of moisture for insects (Jian et al. 2005). Mcgregor (1964) reported that the red flour beetle adult (*Tribolium castaneum* (Herbst)), a common stored grain insect pest in the world, preferred wheat with high dockage content. He mentioned that insect multiplication increased rapidly by increasing the percentage of dockage in wheat. Cracked and broken wheat kernels are more favorable than whole wheat kernels for rusty grain beetle (*Cryptolestes ferrugineus* (Stephens)), another common stored grain insect pest in the world (Watters 1969). Another study by Sinha (1975) showed that the proportion of eggs developed to adults in external infesters of grain like rusty grain beetle increased in the presence of dockage. Jian et al. (2005) found that rusty grain beetles preferred the locations with higher than 10% dockage in wheat. In addition, a high percentage of dockage decreased beetle movement speed that could be another sign that the beetles preferred to stay longer in locations with a higher content of dockage.

Most stored grain fungi are not able to develop in dry grain. However, DFM with higher moisture content than the main grain, as well as broken kernels, provide suitable conditions for some stored grain fungi and microbial infection to grow (Hagstrum et al. 2012; Jian et al. 2005). These components are the first components in the bin that become infected by main stored grain fungi such as *Penicillium* species. Fungi and microbial activities in grain bin develop a high temperature in grain and result in heating. Sour or musty odors are the results of grain heating in bins (United States Department of Agriculture 2016). Musty odors and sour odors in grain during storage in bin indicate fungal activity and fermenting due to microbial activity, respectively (United States Department of Agriculture 2016). Heating should not be mistaken with warm grain due to the hot weather. Heating in wheat during storage in bins may result in kernel discoloration. Heat damaged kernels are considered damaged kernels due to less quality than sound kernels (United States Department of Agriculture 2016).

It has been reported that generally speaking, the moisture content of DFM is higher than the grain kernels (Hagstrum et al. 2012). Prasad et al. (1978) indicated that the average moisture content of rapeseed dockage was significantly higher than the rapeseed kernel itself. On the contrary, the moisture content of dockage in wheat was less than the whole wheat kernels. Athanassiou and Buchelos (2020) reported that more insects were found in the central zone of wheat bin where it is warmer and had lower bulk density (due to fine particles segregation). However, insects still tend to accumulate in the center of grain bin early in the storage period when the entire bulk grain has the same temperature level. This behavior could be due to the accumulation of fine particles in the center of bin (Arbogast et al. 1998; Athanassiou and Buchelos 2020).

2.5.4. Quality change

The quality of grain is affected by many parameters such as genetic traits, growing and harvesting conditions, harvesting and handling equipment, and storage and drying systems. Generally, quality measurement of the grains can be separated into three below groups (Hagstrum et al. 2012) and based on the final use of the grain each quality trait may become more important.

1. Physical traits related to physical properties and appearance of grains such as kernel size, test weight, and moisture content.
2. Sanitary traits related to the cleanliness of grains, for instance, the percentage of undesired materials such as DFM, insects, fungi, mycotoxin, and toxic seeds.
3. Intrinsic traits such as protein, gluten, oil and starch content, milling yield, hardness, and percentage of germination.

Grain grading systems in many countries, including Canada, have high-quality standards for grading grains based on sanitary qualities, i.e., the level of foreign materials allowable in a specific grade of grain. For instance, in Canada, the Canadian Grain Commission under the Canada Grain Act specifies the maximum limits of total foreign material, including other seeds for all grades of Canada Western Red Winter (CWRW) wheat as: No.1, 0.4%; No.2, 0.7%, and No.3, 1.3% (Canadian Grain Commission 2019). In the United States, the Federal Grain Inspection Service (FGIS) investigates the quality of grains by the U.S. Grains Standard Act (USGSA) in terms of quality characteristics, damage and foreign materials. In order to achieve a grade, the grain needs to meet the minimum level for each characteristic specified for that grade (Hagstrum et al. 2012). Grading wheat is usually based on primary grading factors such as test weight, foreign materials, shrunken and broken kernels, damaged kernels and protein content (Canadian Grain Commission 2019). Uneven distribution of DFM in grain bins during loading can affect the grade assigned to that grain. Generally, fines and dense particles and dust accumulate in the center of bin (Chang et al. 1986; Tang and Puri 2004). During unloading bins from bottom, due to funnel flow of grain, the first few batches of grain transported will contain more fines and dust and, accordingly, low grain quality with a lower market value (Fig. 2.15) (Narendran 2018). If a grade has previously been assigned to that grain before loading into the bin, then the first unloaded batches of grain will have a lower value than the desired grade. If a grade is going to be assigned to the grain, because of the high percentage of impurities in the tested grain (that first comes out of the bin), a wrong grade (with a lower value) will be assigned to the whole bin of grain. Moreover, in wheat trading and milling industry, bulk density (test weight) and thousand kernel weight are considered important indicators of milling potential. Segregation in bins may affect these indicators in some parts of the bin and therefore, downgrade the quality of grain (Wang & Fu 2020).

2.6. Objectives

Based on the literature review, segregation of particles in a small batch of a grain mixture could be different compared to the segregation of particles in a big batch of the same grain mixture with the same portion of different particles (Jian et al. 2019). Besides, the segregation of particles in bulk grain in farm bins can be different from the experiments done in laboratory-scale bins when DFM is added manually to the grain. Conducting a segregation study of bulk grain in the real condition is time-consuming and costly because a large amount of grain is required. This research was done to fill the knowledge gap in previous studies as also reported by Jian et al. (2019) who emphasized that the segregation of DFM in bulk grain in large bins should be studied. Therefore, the main objective of this project was to study the distribution of DFM in bulk wheat loaded into a 10-m diameter farm bin by following the loading methods typically used by most Canadian farmers. The detailed objectives were to:

- determine the radial distribution of DFM inside a 10-m diameter grain bin;
- investigate the effect of drop height on the radial distribution of DFM in the bin;
- determine the effect of drop height on the in-situ filling angle of repose;
- measure the radial distribution of wheat kernels of differences in size, sphericity, and true density; and
- determine the effect of segregation on wheat test weight (bulk density) and thousand kernel weight.

3. MATERIALS AND METHODS

3.1. Grain preparation

Three hundred tonnes of Canada Western Red Winter (CWRW) wheat harvested in 2019 from south Manitoba in Canada (Letellier) was used in this study (Fig. 3.1). Canada Western Red Winter wheat is a medium-hard to hard red wheat offering very good milling quality. It is the most grown wheat in western Canada, with 75% of the total annual production of wheat (Canadian International Grains Institute 2019). Canada Western Red Winter wheat was chosen as a representative of bread wheat grown in Canada. It is offered in three milling grades (Table 1.1). Wheat that was used in this study was grade number two that based on the Canadian Grain Commission grading system has maximum 0.7% total amount of foreign materials and 5% total shrunken and broken kernels (SBK) (Table 1.1). The maximum measured percentage of total impurities (including dockage, foreign materials, and shrunken and broken kernels) in wheat was 0.804 ± 0.084% by weight (table 3.7). The initial moisture content of wheat at the time of loading was 12.2 ± 0.4% (w.b.).

Fig. 3.1. Clean (left) and unclean (right) CWRW wheat used in this study.

3.2. Grain bin

A flat-bottom cylindrical steel bin with 10 m diameter, 5 m height of cylindrical part, and 2 m height of conical roof was used (Fig. 3.2). The total volume of the cylindrical part of the bin was about 392 m^3 with a holding capacity of approximately 325 tonnes of wheat (with determined average test weight of 830 kg/m^3). The bin had four manholes of 0.6 m diameter in the roof, and 0.4 m distant from the eaves along four perpendicular radii aligning with north, south, east and west directions. There was one 1.2 m diameter hole at the top center of the conical roof for loading the grain. The floor of the bin was covered by perforated steel.

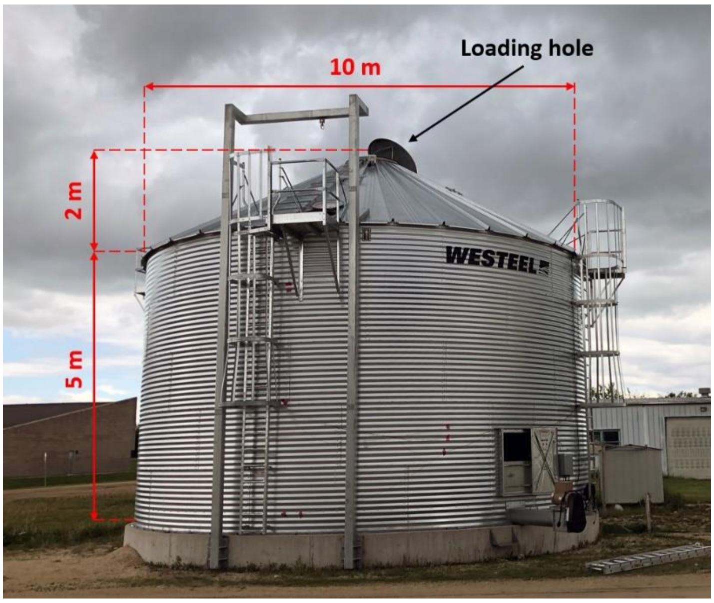

Fig. 3.2. The flat bottom bin that was used for this study.

3.3. Loading wheat into the bin

Wheat was delivered to the bin starting from August 8, 2019. Every other day, two grain trucks delivered 60 tonnes wheat to the site for five days. Grain was loaded from the trucks to the bin using a grain auger (Westfield WR 80-61, Ag Growth International (AGI), Winnipeg, Manitoba, Canada) with 0.2 m diameter and average filling rate of 45 tonne/h (12.5 kg/s) (Fig. 3.3).

Fig. 3.3. A grain auger was used to load wheat from the grain truck into the bin.

To ensure that wheat was loaded into the bin in a vertical direction and the particle trajectories during loading were not affected by the auger, a metal funnel was attached through the top hole (Fig. 3.4). The top dimension of the square funnel was 0.8 m by 0.8 m to cover approximately throughout the 1.2 m diameter hole. The dimensions of the bottom opening of the funnel were 0.2 m by 0.3 m to ensure that the funnel opening was big enough (bigger than the auger diameter of 0.2 m) to let the grain stream move constantly without being clogged. Total height of the funnel was selected 1 m to ensure that wheat was loaded vertically. As discussed in the literature review, the initial direction of the grain stream loaded into a bin plays an important role in the segregation of particles. Therefore, when wheat was supplied by the auger, this funnel prevented the grain from loading into the bin in an inclined direction. The height from the lowest part of the funnel to the bottom of the bin was 6 m.

Fig. 3.4. The funnel attached to the top center of bin.

3.4. Angle of repose of wheat

Sampling was conducted the next day after loading wheat when dust inside the bin settled down. Before sampling, the in-situ filling angle of repose was measured after heap formation for each loading of wheat. In-situ filling angle of repose considers the effect of compaction in grain mixture caused by different drop heights and it can be different from filling angle of repose that measured in laboratory. The filling angle of repose was measured in the mid locations (Fig. 3.5 right) on three radii (120° separated from each other) using an inclinometer with 1° resolution (model 36 Magnetic Polycast Protractor, Empire Level, Mukwonago, Wisconsin, USA). Since wheat was loaded from the top center of bin through the installed funnel, the formed pile was symmetrical and measurements along different radii were considered replicates. To ensure that the inclinometer was laid precisely on the grain surface, a 20 by 40 cm metal plate was used (Fig. 3.5 left).

Fig. 3.5 Inclinometer (left) and the location for measuring the filling angle of repose (right).

3.5. Sampling Procedure

Figure 3.6 shows the sampling pattern for each layer. To avoid disturbing the wheat heap, a plywood board (0.50 m × 0.70 m) was laid in the direction of the desired radius on the surface of the heap in contact with the wall of the bin. Then, three plywood boards (0.50 m × 1.38 m) with a 0.30 m diameter hole in them (for inserting sampling cylinder (tube)) were laid on the surface of wheat heap by the top of the first board against the bottom of the second board (Fig. 3.7 left). There was a total of three holes (0.30 m in diameter) on the plywood boards for sampling locations 2, 3, and 4 on each radius. The distance between every two holes was 1.38 m in the inclined direction of the heap surface. Before sampling at each location, a cardboard cylinder with 29 cm inner diameter, 5 mm thickness, and 50 cm height was pushed vertically through the hole into the bulk grain (Fig. 3.7 right). Wheat inside the cylinder was collected using a scoop. Samples were collected at four locations (locations 2, 3, 4, 5) along three radii of wheat heap (different from the radii which were used to measure the angle of repose), and one sample at the center of bin (location 1). Radii were separated 120° from each other (Fig. 3.6). Table 3.1 shows the horizontal distance of sampling locations on radii from the center of bin and Table 3.2 shows the different zones of the bin that were used to determine the radial distribution of DFM. In this study distance from center means horizontal distance of sampling locations from the center of bin, not the inclined distance along the heap.

As was discussed in segregation mechanisms, top-to-bottom segregation such as fluidization may occur in the presence of fine particles when grain is loaded from height. To study this top-to-bottom segregation, two samples were taken at each location, one from the top half and another from the bottom half of the 50-cm long sampling cylinder. Each sample weighed about 11 kg. Since wheat was loaded to the center of bin in a vertical direction (using installed funnel to the top hole of the bin (Fig. 3.4), the formation of wheat pile was symmetrical and therefore, the samples that were collected at the same location (locations 2, 3, 4 and 5) and position (top or bottom of cylinder) but on different radii were considered replicates. Therefore, sampling along three radii represent three replicates. Collected samples were labeled and kept in double plastic bags at room temperature for analyses (Fig. 3.8 right). From each layer, 26 samples (two samples each from 13 locations) were collected.

After sampling, wheat heap was leveled using grain shovel to be ready for the next loading. Before the next loading, height from the bottom of the funnel to the surface of leveled grain was measured (maximum height). Similarly, height from the bottom of the funnel to the peak of the grain heap was measured after loading (minimum height). These measured heights were used to calculate the drop height of grain during loading. The average of the maximum and minimum drop heights was considered grain drop height for that layer (Fig. 3.9, Table 3.3). The whole procedure was repeated for each loading until the last layer of the grain (layer 5) formed in the bin. Totally, 130 samples were taken from five layers of grain loading.

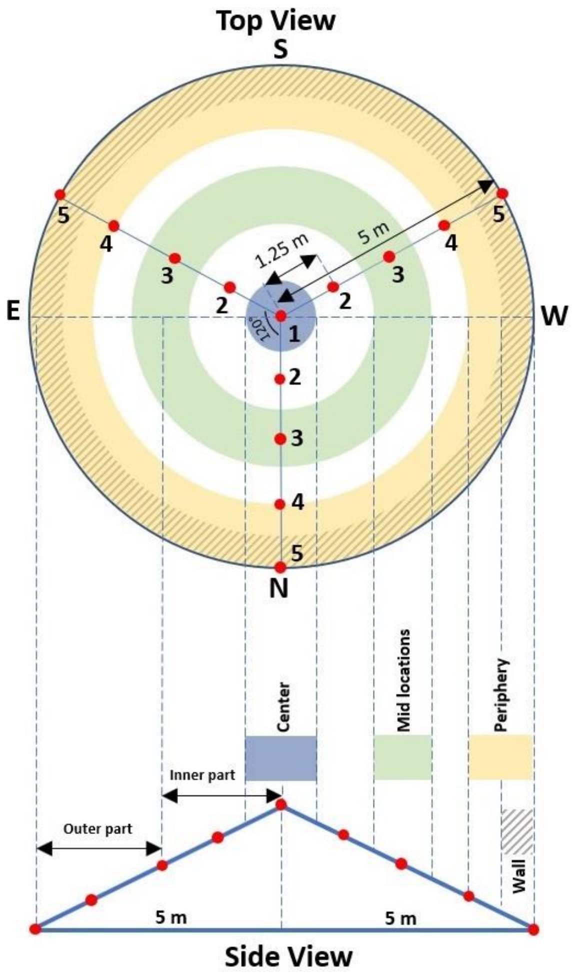

Fig. 3.6. Sampling pattern and bin zones for each layer of wheat.

Table 3.1. The horizontal distance of sampling locations from center of bin.

Location	Horizontal distance from center of bin (m)
1	0.00
2	1.25
3	2.50
4	3.75
5	5.00

Table 3.2. Different zones of the bin.

Horizontal distance from center of bin (m)	Zone
0.00 – 0.625	Center
0.00 – 2.5	Inner part of the bin
1.875 – 3.125	Mid locations
2.50 – 5.00	Outer part of the bin
3.75 - 5	Periphery
4.375 - 5.00	Wall (Close to the wall)

Fig. 3.7. Plywood boards (left) and sampling cylinder being inserted vertically for sampling (right).

Fig. 3.8. Sampling from the bin (left) and collected samples (right).

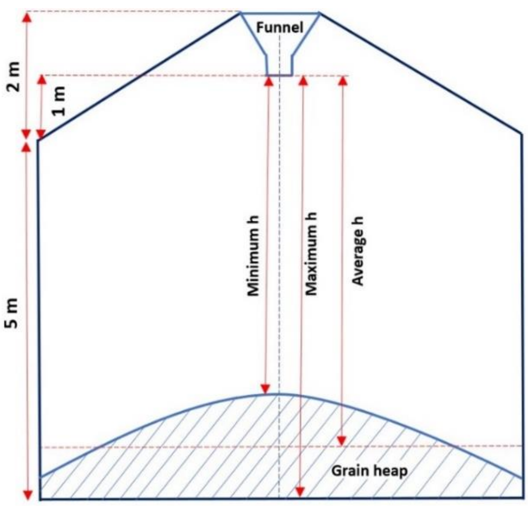

Fig. 3.9. Drop height of grain for each layer.

Table 3.3. Drop height of grain for each layer.

Layer	Drop height (m)		
	Min	Max	**Average**
1	4.4	6.0	**5.2**
2	3.5	5.1	**4.3**
3	2.6	4.2	**3.4**
4	1.7	3.3	**2.5**
5	0.8	2.4	**1.6**

3.6. Separating impurities (DFM and SBK) from wheat

Impurities can be removed from wheat using hand sieves, mechanical sieve shaker or mechanical dockage tester. A horizontal circular motion sieve shaker (model AS400, Retsch, Haan, Germany) (Fig. 3.10) with five different sieve sizes was used to separate particles larger and smaller than wheat kernels. Stainless steel sieves number 5, 6, 7, 10, 12, and 50 (ASTM standard) were fixed on the shaker (in the order from largest opening at the top and the smallest opening at the bottom) (Table 3.4). Table 3.4 shows the opening size of each sieve and different particles that can be separated. These sieves were selected based on the particle size distribution in wheat. Sieve number 10 with opening of 2 mm (5/64 inch) diameter suggested by the United States Department of Agriculture was used to retain sound wheat kernels. The maximum capacity of the shaker for each run was 5 kg, but a smaller batch of grain was used to allow the shaker to operate in the optimum condition of sieving. Therefore, each sample (that weighed about 11 kg), was divided into four batches (each weighed about 2.5 – 3 kg) to feed into the shaker. The optimum operating condition of sieve shaker was determined by trial and error so that the shaker was operated at 200 rpm for 3 min for each run. Collected particles in each sieve were weighed using a balance with 0.001 g resolution.

Fig. 3.10. Retsch, model AS400 sieve shaker used for separating impurities from wheat.

Table 3.4. Sieves that were used for separating impurities from wheat.

Sieve Number (ASTM standard)	Sieve opening (mm)	Particles which remain on the top of the sieve
5	**4.00**	larger particles like spikelet
6	**3.35**	other grains (corn and soybean) + particles such as stones, straw, internode, knuckle, rachis, spikelet, chaff, stem, and parts of other wild plants
10	**2.00**	all sound wheat kernels + foreign materials (wild oat kernels + particles roughly as big as wheat kernels)
12	**1.70**	shrunken and broken wheat kernels + small amount of large canola kernels and fine particles
50	**0.30**	small particles such as small chaff and awn + canola kernels + small broken wheat kernels
Tray	**-**	Dust + fragments of particles

Figure 3.11 shows some particles that were removed from the wheat samples. A portion of impurities in the wheat samples were roughly the same size as wheat kernels which are called foreign materials because it is difficult to separate them using sieves. These particles which included wild oat, straw, internode, knuckle, rachis, broken soybean, and stem of other

wild plants were separated from wheat retained in sieve 10 by handpicking and were added to the rest of large impurities (except stones and other grains) that were referred to as other particles. Also, stones and other cereals (corn and soybean) that retained in sieve 10 were added to stones and other grains, respectively. Large wheat kernels that retained in sieve 6 were separated by hand from other impurities and were added to sound wheat kernels. Impurities in each sieve were separated into different groups as defined in Table 3.5 and shown in Fig. 3.12. While there were some studies on the distribution of other grains, fine particles, and dust in bulk grains, no study was found to specifically investigate the distribution of SBK in bulk grains. The percentage of each group in samples (Table 3.5) was calculated by the ratio of the weight of related particles to the weight of the initial sample. The sum of the DFM and SBK removed from each sample was referred to as total impurities. Total impurities were divided into two groups, one larger than or equal to wheat kernels (≥ 2.00 mm), and second smaller than wheat kernels (< 2.00 mm) and these were referred to as large impurities and small impurities, respectively (Table 3.5). After removing all DFM and SBK, wheat was referred to as clean wheat. A sieve number 7 with an opening of 2.80 mm was used to separate clean wheat into two groups of small and large kernels. Wheat kernels that were retained in this sieve were considered large wheat kernels, and those that passed through the sieve were considered small wheat kernels (Fig. 3.13). Sieve 7 with was used for separating small kernels from large kernels based on the fact that the average of the lowest dimension of wheat kernels (thickness) was found to be 2.77 mm. So, the kernels with a bigger dimension of this critical value were considered large kernels.

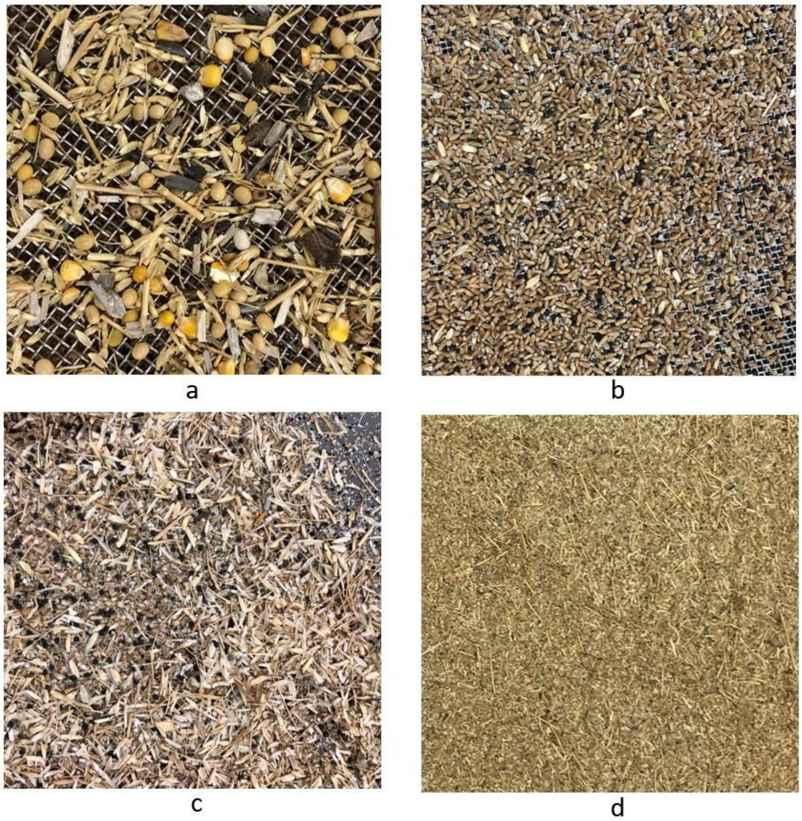

Fig. 3.11. **a)** Impurities on the top of sieve NO. 6, **b)** SBK and large canola kernels on the top of sieve NO. 12, **c)** Fine particles on the top of sieve NO. 50, **d)** Dust and fragments on the tray.

Table 3.5. Details of dockage and foreign materials (DFM), and shrunken and broken kernels (SBK) in samples.

Impurities		DFM & SBK	Contents
Large Impurities (larger than or equal to wheat kernels) (≥ 2.00 mm)		**Stones**	stone pieces
		Other grains	large grains including corn and soybean
		Other particles	straw, internode, knuckle, rachis, spikelet, large chaff, wild oat kernels and stem, parts of other wild plants
Small Impurities (smaller than wheat kernels) (< 2.00 mm)	≥ 1.70 mm	**Shrunken and broken kernels (SBK)**	shrunken and broken wheat kernels, large canola kernels, and other particles
	≥ 0.300 mm	**Fine particles**	pieces of broken wheat kernels, awn, broken chaff, and canola kernels
	< 0.300 mm	**Dust and fragments**	Dust and pieces of chaff and awn

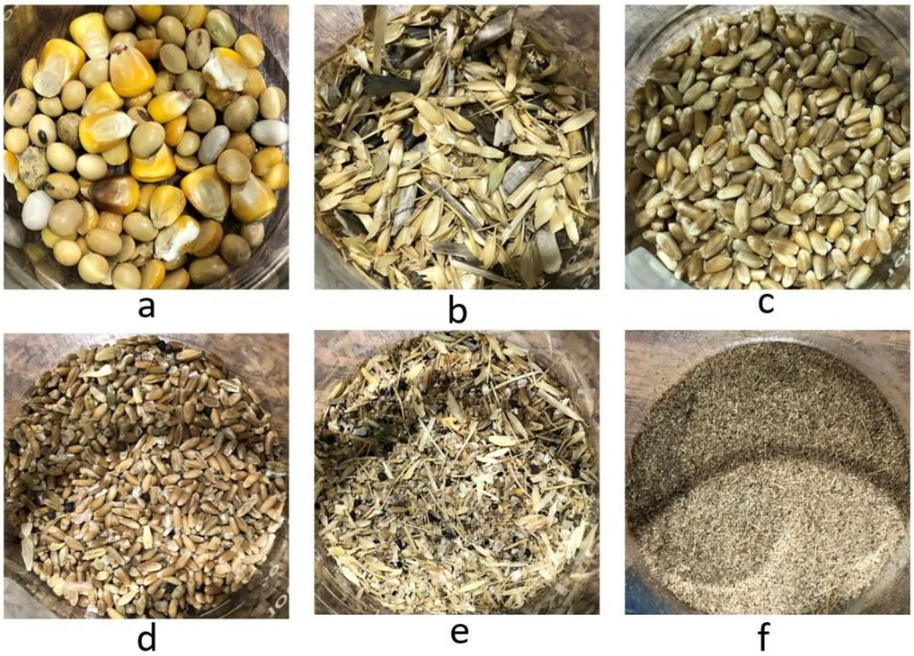

Fig. 3.12. **a)** Other grains, **b)** Other particles, **c)** Clean wheat, **d)** Shrunken and broken kernels, **e)** Fine particles, **F)** Dust and fragments.

Fig. 3.13. Large wheat kernels (left) and small wheat kernels (right).

3.7. Moisture Content

Moisture content (MC) of all collected samples from bin was measured following the ASABE standard (ASABE 2017). About 10 grams of each sample, in triplicate, were randomly selected and weighed and placed in a convection oven (model Thelco, Precision Scientific, Chennai, India) at 130 ± 1 °C for 19 h, and then wet basis (w.b.) moisture content was calculated as the ratio of sample mass loss divided by initial sample mass. The average moisture content of wheat samples at the loading time was 12.2 ± 0.4% (w.b.). The samples were kept in double plastic bags and therefore no change in the moisture content was observed at the time of analyzing samples.

3.8. Test weight (Bulk density)

Bulk density (ρ_b) is defined as the weight of the unit volume of bulk materials. It is calculated as the ratio of sample mass divided by volume occupied by the sample expressed in kg/m^3. In bulk density, the volume of the tested grain includes the volume of the kernels and the volume of intergranular air among the kernels. In this study, the bulk density of collected samples from different locations of bin were measured in laboratory, i.e., any differences that were observed between bulk densities of collected samples were due to the differences in the percentage of segregated particles not due to compaction caused by drop height. The effect of compaction on bulk density due to drop height can be determined by measuring in-situ bulk density which means measuring bulk density in bin without disturbing bulk grain.

In Canada, test weight is used which is a standard method of measuring bulk density in laboratory (Jian et al. 2018). In this study bulk density of collected samples was determined using a test weight apparatus based on the methodology outlined in the Canadian Grain Commission grain grading guide (Canadian Grain Commission 2019). So, instead of bulk density, test weight terminology was used. The test weight apparatus consists of a 0.5 L cylindrical cup, a cox funnel, a striker, and a scale (Fig. 3.14 left). To ensure that a random subsample was taken from the original wheat sample, a Boerner sample divider was used (Fig. 3.14 right). About 0.5 kg sample was used to fill cox funnel to ensure that wheat overflow from the cylindrical cup. Striker was used to remove extra wheat in three zig-zag motions and then weight of wheat in the cup was measured. Test weight of collected samples was measured before and after removing DFM and SBK and presented in kg/m^3. Each experiment was repeated three times. Bulk density of five randomly selected sample of different groups of impurities removed from wheat were also measured with the same test weight method.

Fig. 3.14. Test weight apparatus (left) and Boerner sample divider (right).

3.9. True density

True density (particle density or kernel density) (ρ_t) is defined as the ratio of mass of grain kernels to the volume occupied by them. It is measured as the weight of a grain sample divided by volume occupied by kernels (excluding the intergranular void spaces from total sample volume) (Jayas & Cenkowski 2010). True density is always greater than bulk density because the intergranular void spaces are excluded in the calculation. One of the most precise methods for measuring the true density of grain is to use a gas pycnometer that measures the true volume of the grain samples by employing ideal gas displacement and expansion laws. The true density of collected samples was measured using a gas pycnometer (model ULTRAPYC 1200e, Quantachrome, Boynton Beach, Florida, USA) (Fig. 3.15) before and after removing DFM and SBK from samples. About 30 - 35 g of wheat was randomly selected from samples that had already been subsampled by the Boerner sample divider for measuring test weight. To enhance the accuracy, pycnometer was set in a way that repeated the true density readings three times and gave the average value. The true density of five randomly selected samples of different groups of impurities removed from wheat was also measured in the same way.

Fig. 3.15. Gas pycnometer for measuring the true density of samples.

3.10. Porosity

Porosity is the ratio of intergranular void volume to the total volume of the bulk grain. It is calculated from the measured bulk density (ρ_b) and true density (ρ_t) of grain using Equation 3.1 and is expressed in percent (Jayas & Cenkowski 2010; Mohsenin 1986).

$$\varepsilon = [1 - \frac{\rho_b}{\rho_t}] \times 100 \quad (3.1)$$

Where

ε is porosity (%),

ρ_b is bulk density (kg/m^3),

ρ_t is true density (kg/m^3).

ε is porosity (%).

3.11. Kernel dimensions and sphericity

Dimension of kernels can affect the milling yield of wheat. It has been reported that larger kernels will have a higher milling yield (Baasandorj et al. 2015). Length (L), width (W), and thickness (T) (Fig. 3.16) of ten randomly selected wheat kernels from each clean sample were measured using digital calipers with 0.01 mm resolution (Jian et al. 2018). The sphericity of kernels was calculated by equation 3.2 (Krumbein 1941).

$$\Psi = \frac{(LWT)^{1/3}}{L} \tag{3.2}$$

Where

Ψ is sphericity (dimensionless),

L is kernel length (mm),

W is kernel width (mm),

T is kernel thickness (mm).

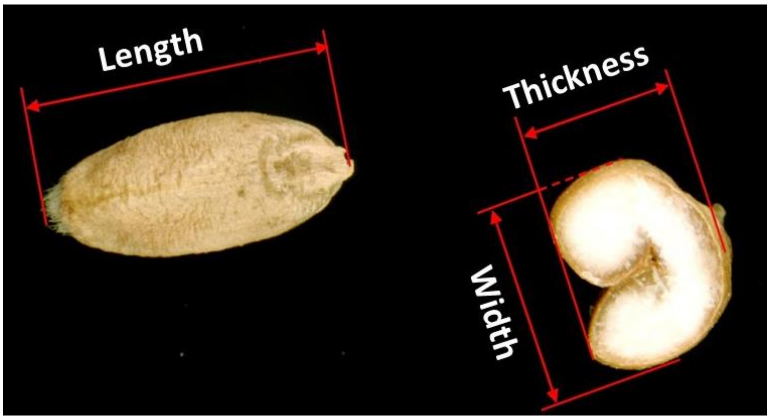

Fig. 3.16. Representation of measured length (L), width (W), and thickness (T) of a wheat kernel (Wasilewska et al. 2015).

3.12. Thousand kernel weight (TKW)

Thousand kernel weight is the weight of 1000 wheat kernels, which is used to determine the milling yield of grain (Tilley et al. 2012). Larger kernels will result in a higher TKW and may germinate more successfully (Valencia-Diaz et al. 2015; Wu et al. 2018) or may have a higher milling yield (Baasandorj et al. 2015; Tilley et al. 2012; Wang & Fu 2020; Wu et al. 2018) or better baking characteristics (Morgan et al. 2000). One thousand clean wheat kernels of each sample were randomly selected, counted, and then weighted using a 0.001 g precision digital balance. In order to count the exact number of kernels in a short time, a holder plate with 216 slots (8 mm × 4 mm) was used (Fig. 3.17). For this purpose, first, a batch of wheat (weighed about 200 g) was randomly selected from clean wheat that had already been divided by Boerner sample divider and then was poured on the surface of the holder plate. Then if there were empty slots or slots with more than one kernel, a kernel was placed in empty slots using a tweezer, and/or extra kernels were removed. This procedure was repeated to count 1000 kernels.

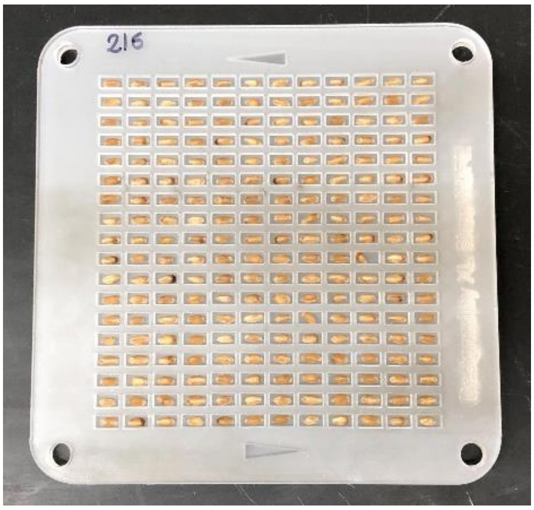

Fig. 3.17. Counting 1000 kernels using a kernel holder plate.

3.13. Statistical analysis

The experiments were conducted using a three way factorial design with three replicates to study the effect of three treatment factors on the radial distribution of DFM and SBK in the bin: five levels for drop height (5.2, 4.3, 3.4, 2.5, 1.6 m from the bottom of the loading funnel), five levels for sampling location on radius (0.00, 1.25, 2.50, 3.75, 5.00 m horizontal distance from the center of bin), and two levels for sampling position (top or bottom of the sampling cylinder). Besides, the effect of segregation on changes in test weight (bulk density), true density, porosity, thousand kernel weight, kernel dimensions, and sphericity in the radial direction was determined. Analysis of variance (ANOVA), student t-test, and Tukey test (for pairwise comparison) were used to study the effects of factors. The level of significance was set at α=0.05. In case a tested factor did not have a significant effect, the data associated with that factor were pooled. Finally, to determine the trend of changing dependent variables, Pearson correlation coefficient (r) was used. Statistical analysis software SigmaPlot (Version 11.2.0.5, Systat Software Inc., California, USA) was used to conduct the analysis.

Measurements and then statistical analysis showed that the percentage of total impurities in each layer of loading were significantly different (Table 3.6). These differences may be due to differences in the growing field, harvest machinery, storage bins, etc. Table 3.7 shows a pairwise comparison of the percentage of large and small impurities as well as total impurities between layers of loading. The percentage of large, small and total impurities were significantly different between layer five and other layers except layer three. Also, a significant difference between layers one and three was observed for large impurities and total impurities but not for small impurities. Therefore, to study the effect of drop height on dependent variables, normalized values for each parameter based on the average data of each layer were calculated using Equation 3.3 (Jayas et al. 1987; Narendran et al. 2019). A normalized value higher than one, indicates a higher than the average of the layer for that sample. In addition, no trend was observed in the values of total impurities, large impurities, and small impurities between the top and bottom positions at each sampling location for different layers. Therefore, data associated with the top and bottom at each sampling location were pooled. After pooling the data, a two-way ANOVA was conducted to study the effect of drop height and sampling location on the radial distribution of impurities.

$$Normalized\ value\ in\ the\ sample = \frac{Measured\ value\ in\ the\ sample}{Average\ value\ in\ that\ layer} \quad (3.3)$$

Table 3.6. The results of ANOVA of the percentage of total, large, and small impurities among different layers of loading.

Impurities	SV	DF	F	P-value
Large	**Layer**	4	10.189	<0.001
	Error	125		
	Total	129		
Small	**Layer**	4	7.154	<0.001
	Error	125		
	Total	129		
Total	**Layer**	4	9.152	<0.001
	Error	125		
	Total	129		

Table 3.7. Pairwise comparison (Tukey test) of the percentage of total, large, and small impurities between two different layers of loading.

Layer	Large impurities (%)	Small impurities (%)	Total impurities (%)
1	0.092 ± 0.009 a	0.309 ± 0.020 a	0.401 ± 0.023 a
2	0.139 ± 0.010 bc	0.333 ± 0.023 a	0.473 ± 0.028 ab
3	0.158 ± 0.012 cd	0.445 ± 0.057 ab	0.603 ± 0.066 bc
4	0.111 ± 0.012 ab	0.376 ± 0.029 a	0.487 ± 0.030 ab
5	0.188 ± 0.016 d	0.616 ± 0.077 b	0.804 ± 0.084 c

Means with the same letter in each column are not significantly different from each other (P<0.05).

4. RESULTS AND DISCUSSION

4.1. Angle of repose

The average (for all drop heights) of in-situ filling angle of repose of the grade two CWRW wheat at 12.2 ± 0.4% MC (w.b.) was 22.9 ± 1.4° which is similar to 24.3 ± 6.7° in-situ filling angle of repose reported for hard red winter wheat at 11.5 ± 0.7% MC measured in USA farm bins (Bhadra et al. 2017), and also similar to 24.3 ± 0.6° (for clean wheat) but smaller than 27.4 ± 0.6° (for 7.5% insect-infested wheat) measured for USA hard red winter wheat at 11.7 – 13.4% MC in laboratory (Bian et al. 2015). It was also similar to 25 ± 0.4° to 26 ± 0.4° reported for three variety of Canadian hard red spring wheat at 12.7% MC (Muir and Sinha 1988). The difference between measured angle of repose could be due to the difference in wheat variety, moisture content, percentage and size of DFM, or drop height of the wheat. The filling angle of repose of wheat was less than 30°, so it is considered a freely flowable grain (Teferra 2019).

It is expected that compaction in wheat mixture increases by increasing drop height and consequently the angle of repose increases. However, in this study, the in-situ filling angle of repose was significantly higher at the lowest drop height (1.6 m) than at the highest drop height (5.2 m), while no difference was observed at other drop heights (Table 4.1). This might be caused by the differences of the total impurities (including dockage and foreign materials) in different layers of loading. Table 4.1 shows that the percentage of total impurities which mainly was comprised of small impurities (table 3.7) in layer 5 (1.6 m drop height) was noticeably higher than the percentage of total impurities in layer 1 (5.2 m drop height). As it was discussed in chapter 2, the main reason for differences in the angle of repose of non-cohesive particulate materials such as bulk grain is the variation in the shapes and sizes of particles in grain mixture. Irregular-shaped and sharp-edged particles such as dockage have a higher angle of repose compared to rounded particles such as wheat kernels (Fu et al. 2020). Also, generally, fine particles due to stronger adhesive forces can form a steeper heap compared to larger particles (Fig. 2.14 right) (Schulze 2008; Shimoska et al. 2013; Teferra 2019). Therefore, presence of these particles (dockage, foreign and fine materials) in bulk grain will result in a higher filling angle of repose. Another reason for the difference between the in-situ angles of repose of wheat for 1.6 m and 5.2 m drop height could be that by increasing drop height, particles with a higher momentum hit the apex of the wheat pile and therefore increased the impact segregation, pushed away the other particles and made the apex flatter. However, the effect of presence of dockage and foreign materials in bulk wheat seems to be more noticeable. To study the effect of drop height on in-situ angle of repose of bulk grain, the percentage of dockage and foreign materials needs to be kept constant for all drop heights or a factorial experiment with different layers of drop height and percentage of total impurities needs to be conducted. In this study, the percentage of total impurities of different layers of wheat during loading was not possible to be controlled, so the effect of drop height on the in-situ filling angle of repose could not be concluded from collected data.

Table 4.1. Pairwise comparison (Tukey test) of the in-situ filling angle of repose and the average of total impurities at different drop heights.

Layer	**Drop Height (m)**	**Filling Angle of Repose (°)**	**Average of measured total impurities (%)**
1	**5.2**	20.7 ± 0.6 a	0.401 ± 0.023 a
2	**4.3**	23.3 ± 0.6 ab	0.473 ± 0.028 ab
3	**3.4**	22.7 ± 0.6 ab	0.603 ± 0.066 bc
4	**2.5**	23.3 ± 0.6 ab	0.487 ± 0.030 ab
5	**1.6**	24.7 ± 0.6 b	0.804 ± 0.084 c

Means with the same letter in each column are not significantly different from each other ($P<0.05$)

4.2. Distribution of large, small, and total impurities

Drop height significantly influenced the radial distribution of small impurities and total impurities in the bin, while the distribution of large impurities was not significantly affected by drop height (Table 4.2). Similar results were reported by Narendran et al. (2019) that the loading height significantly influenced the distribution of canola (smaller than wheat kernels) but did not influence the distribution of kidney beans and soybeans (larger than wheat kernels) in wheat mixture. Also, similar result for small impurities but contradictory result for large impurities were reported by (Parker et al. 2005) that drop height (0.65, 1.30, and 1.95 m) significantly affected the distribution of both components larger and smaller than wheat in a wheat mixture. This contradiction could be due to the size difference or small amount of large impurities in the current study.

Figures 4.1b and 4.1c illustrate that drop height had the maximum effect on the accumulation of small impurities and total impurities in the center compared to other locations of the bin. It can be seen that the percentage of small impurities and total impurities fluctuated considerably in the center of bin by increasing drop height. In the center of bin, total impurities showed the same changing trend as small impurities because the large part of total impurities is comprised of small impurities (impurities smaller than wheat kernels). The percentage of small impurities in wheat (0.416 ± 0.022%) was significantly higher than large impurities (0.138 ± 0.006%) (Table 4.3). By increasing drop height, the uniformity of distribution of small and total impurities in different locations of the bin fluctuated for drop height between 1.6 to 3.4 m and then increased from drop height between 3.4 to 5.2 m. A similar result that the radial uniformity of fine particles increased with increasing drop height was reported (Drahun and Bridgwater 1983). One reason behind more uniformity of small impurities at higher drop heights could be that the velocity of the particles in the flowing layer of wheat on the heap surface increases at higher drop heights and therefore gives less time to the small particles to prelocate between large particles in locations near the center of bin. On contrary to this study, Chang et al. (1986) reported that two different drop heights (4.4 m and 7.4 m) had no significant effect on the distribution of fine particles in corn. Jayas et al. (1987) also observed no difference in the distribution of chaff and fine particles in canola by changing the drop height between 3 to 7 m.

Small impurities and therefore total impurities were by far concentrated in the center of bin (Fig. 4.1b and Fig. 4.1c) while large impurities were mostly found in the center and periphery of the bin (Fig. 4.1a). Parker et al. (2005) reported similar results that fine particles smaller than wheat kernels accumulated more in the center of bin, however particles larger than wheat kernels were more found only close to the walls. The concentration of small particles in the center of bin agrees with previous studies (Chang et al. 1986; Nourmohamadi-Moghadami et al. 2020; Tang & Puri 2004). Small impurities in all drop heights were highly accumulated in the center and dramatically decreased from the center to only 1.25 m away from the center (Fig. 4.1b). Total impurities followed the same trend as small impurities. Large impurities gently reduced from the center of bin to mid locations and then increased to almost the same initial level close to the wall (Fig. 4.1a). Table 4.4 shows the correlation between the percentage of large, small, and total impurities with the horizontal distance from the center of bin. There was a significant negative correlation between small and total impurities with the horizontal distance from the center of bin for all drop heights (except 5.2 m drop height for total impurities). This means that generally by moving from the center of bin toward the wall, the percentage of small impurities, as well as total impurities, decreased while the percentage of large impurities increased.

The average value of total impurities in the bin was 0.554 ± 0.026%. Figure 4.1 proves the intensity of segregation in the center of bin which may result in downgrading quality of wheat or increasing airflow resistance in the core of the bin. If wheat has higher percentage of dockage, segregation in the center of bins could even be worse.

Table 4.2. Effect of drop height and horizontal distance from center of bin on the distribution of large, small and total impurities (two-way ANOVA).

Impurities	Source of Variation	DF	F	P-value
Large	**Height**	4	2.142	0.081
	Distance	4	189.400	<0.001
	Height × Distance	16	16.98	<0.001
Small	**Height**	4	16.467	<0.001
	Distance	4	622.008	<0.001
	Height × Distance	16	27.078	0.003
Total	**Height**	4	10.539	<0.001
	Distance	4	499.940	<0.001
	Height × Distance	16	18.732	<0.001

Table 4.3. Pairwise comparison (Tukey test) of the percentage of large, small, and total impurities among different locations (horizontal distances from the center) of the bin for each drop height.

Drop Height (m)	Location (m)	Large impurities (%)	Small impurities (%)	Total impurities (%)
	0.00	0.120 ± 0.015 a	0.615 ± 0.028 a	0.735 ± 0.036 a
	1.25	0.054 ± 0.008 b	0.349 ± 0.016 b	0.403 ± 0.021 bd
5.2	**2.50**	0.036 ± 0.008 b	0.268 ± 0.016 cd	0.304 ± 0.021 c
	3.75	0.116 ± 0.008 a	0.234 ± 0.016 c	0.349 ± 0.021 cd
	5.00	0.152 ± 0.008 c	0.285 ± 0.016 d	0.437 ± 0.021 b
	0.00	0.183 ± 0.015 a	0.637 ± 0.028 a	0.820 ± 0.036 a
	1.25	0.129 ± 0.008 b	0.416 ± 0.016 b	0.545 ± 0.021 b
4.3	**2.50**	0.080 ± 0.008 c	0.287 ± 0.016 c	0.368 ± 0.021 c
	3.75	0.129 ± 0.008 b	0.224 ± 0.016 d	0.352 ± 0.021 c
	5.00	0.205 ± 0.008 a	0.305 ± 0.016 c	0.510 ± 0.021 b
	0.00	0.291 ± 0.015 a	1.402 ± 0.028 a	1.693 ± 0.036 a
	1.25	0.210 ± 0.008 b	0.433 ± 0.016 b	0.643 ± 0.021 b
3.4	**2.50**	0.102 ± 0.008 c	0.308 ± 0.016 c	0.410 ± 0.021 c
	3.75	0.115 ± 0.008 c	0.329 ± 0.016 cd	0.444 ± 0.021 c
	5.00	0.162 ± 0.008 d	0.390 ± 0.016 bd	0.552 ± 0.021 b
	0.00	0.226 ± 0.015 a	0.737 ± 0.028 a	0.963 ± 0.036 a
	1.25	0.065 ± 0.008 b	0.409 ± 0.016 b	0.474 ± 0.021 bd
2.5	**2.50**	0.052 ± 0.008 b	0.317 ± 0.016 c	0.369 ± 0.021 c
	3.75	0.118 ± 0.008 c	0.317 ± 0.016 c	0.435 ± 0.021 cd
	5.00	0.171 ± 0.008 d	0.342 ± 0.016 c	0.513 ± 0.021 b
	0.00	0.240 ± 0.015 a	1.910 ± 0.028 a	2.150 ± 0.036 a
	1.25	0.133 ± 0.008 b	0.545 ± 0.016 b	0.678 ± 0.021 b
1.6	**2.50**	0.108 ± 0.008 b	0.440 ± 0.016 c	0.548 ± 0.021 c
	3.75	0.187 ± 0.008 a	0.416 ± 0.016 c	0.603 ± 0.021 bc
	5.00	0.305 ± 0.008 c	0.631 ± 0.016 b	0.936 ± 0.021 d
	Average	0.138 ± 0.006 x	0.416 ± 0.022 y	0.554 ± 0.026

Means with the same letter in each column associated with the drop height are not significantly different from each other (P<0.05).
Means with the same letter in the average row (based on all 25 values in each column) are not significantly different from each other (P<0.05).

Table 4.4. Correlation coefficient between horizontal distance from center of bin and the percentage of large, small, and total impurities at different drop heights.

Impurities	Drop Height (m)	r	P-value
Large	Pooled data	0.300	<0.001
	5.2	-0.659	<0.001
	4.3	-0.715	<0.001
Small	3.4	-0.549	0.003
	2.5	-0.642	<0.001
	1.6	-0.456	0.019
	5.2	-0.326	0.104
	4.3	-0.460	0.018
Total	3.4	-0.567	0.002
	2.5	-0.369	0.063
	1.6	-0.309	0.124

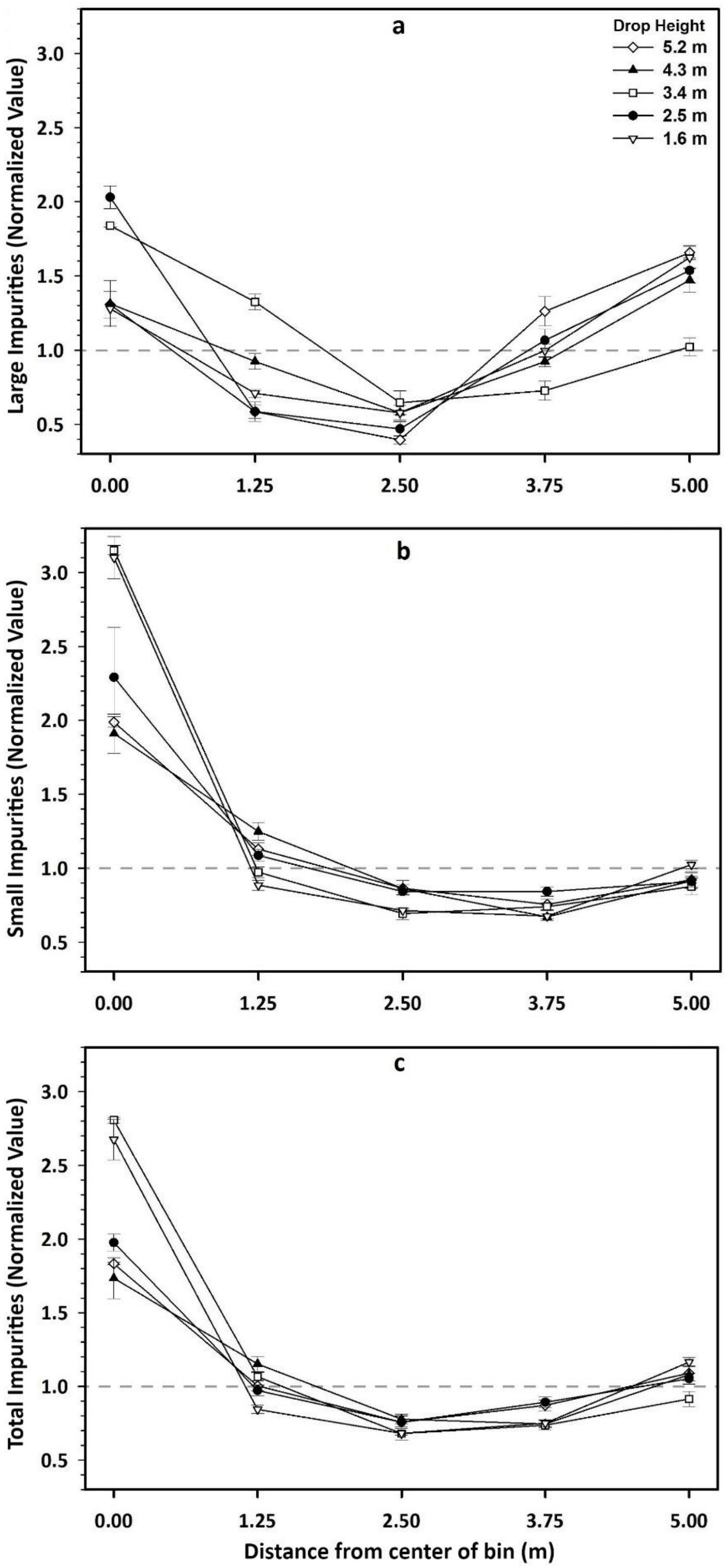

Fig. 4.1. Changes of the normalized value of large, small, and total impurities by horizonal distance from center of bin. Dashed lines show the normalized value (1.0) of the average.

4.3. Distribution of each specific group of impurities in the bin

The greatest portion (weight) of DFM in wheat was fine particles with average percentage of 0.182 ± 0.012%. The percentage of SBK was 0.179 ± 0.005 (Table 4.5). Negligible amount of stones was found in the center location of some layers. The lowest portion was the other grains (including corns and soybeans). Since these different particle groups with different physical properties may have different segregation behavior, the distribution of these particle groups in the bin is discussed in detail in the next subsections.

Table 4.5. Percentage of different particle groups at different drop heights (different layers of the bin).

Impurities	Drop height (Layers are from bottom to top)					
	5.2 m (Layer 1)	4.3 m (Layer 2)	3.4 m (Layer 3)	2.5 m (Layer 4)	1.6 m (Layer 5)	Average
Stones (%)	0.001 ± 0.001 a	0.001 ± 0.000 a	0.001 ± 0.000 a	0.000 ± 0.000 a	0.000 ± 0.000 a	0.000 ± 0.000 a
Other grains (%)	0.014 ± 0.001 b	0.031 ± 0.002 b	0.082 ± 0.013 b	0.010 ± 0.001 b	0.018 ± 0.002 b	0.031 ± 0.003 b
Other particles (%)	0.077 ± 0.009 c	0.108 ± 0.010 c	0.076 ± 0.008 b	0.101 ± 0.012 c	0.170 ± 0.016 c	0.106 ± 0.006 c
Shrunken and broken kernels (%)	0.132 ± 0.006 d	0.146 ± 0.007 d	0.196 ± 0.009 c	0.180 ± 0.007 d	0.240 ± 0.013 d	0.179 ± 0.005 d
Fine particles (%)	0.149 ± 0.013 d	0.157 ± 0.017 d	0.173 ± 0.030 c	0.152 ± 0.013 d	0.279 ± 0.043 d	0.182 ± 0.012 d
Dust and fragments (%)	0.028 ± 0.005 b	0.030 ± 0.006 b	0.076 ± 0.026 b	0.043 ± 0.011 b	0.097 ± 0.033 e	0.055 ± 0.009 b

Means with the same letter in each column are not significantly different from each other (Tukey test, P<0.05)

4.3.1. Stone pieces (Dense particles)

Stone pieces which are a good representative of dense particles, were only found seldom in the center of bin (< 0.001%). At low concentrations of heavy particles, those particles sink in the bulk solids surface causing them to be collected in the center of the heap (Schulze 2008). Based on the U.S. standards, if wheat contains more than four stone pieces or any number of stones that have an aggregate weight of more than 0.1% of the sample weight, the sample does not meet the requirements for grading (United States Department of Agriculture 2016).

4.3.2. Other grains

Mainly corn and soybean kernels found in the samples were referred to as other grains in this study. Drop height did not have a significant effect on the distribution of other grains in the bin (Table 4.6). This result agrees with Narendran et al. (2019) that the loading height did not influence the distribution of kidney beans and soybeans (larger than wheat kernels) in wheat mixture, but it is contradictory to Parker et al. (2005) that drop height significantly affected the distribution of components larger than wheat in a wheat mixture. The percentage of other grains significantly decreased by increasing distance from the center of bin (Table 4.6). Other grains were negatively correlated to the distance from the center of bin ($r=-0.736$, $p<0.001$). They had a maximum amount of 0.066 ± 0.024% in the center of bin (approximately twice the average value) and gradually decreased to 0.015 ± 0.002% by moving away from the center (Fig. 4.2). These results are similar to results reported by Narendran et al. (2019) that kidney beans and soybeans in wheat mixture accumulated mostly in the center and mid locations of the bin but it is contradictory to the study by Parker et al. (2005) that reported the percentage of soybeans in wheat mixture found near the walls were more than the center. The percentage of other grains found in the inner part of the bin (2.5 m or less distance from the center) was more than the average percentage of other grains, while in the outer part of the bin (2.5 m or more distance from the center) the percentage of other grains was less than the average value (Fig. 4.2).

Table 4.6. Effect of drop height and horizontal distance from center of bin on the distribution of other grains (two-way ANOVA).

Source of Variation	DF	F	P-value
Height	4	0.840	0.503
Distance	4	67.693	<0.001
Height × Distance	16	5.139	<0.001

Table 4.7. Pairwise comparison (Tukey test) of the percentage of other grains at different horizontal distances from center of bin.

Horizontal distance from center (m)	Other grains (%)
0.00	0.066 ± 0.024 a
1.25	0.051 ± 0.011 a
2.50	0.029 ± 0.005 b
3.75	0.017 ± 0.002 b
5.00	0.015 ± 0.002 b

Means with the same letter are not significantly different from each other (P<0.05)

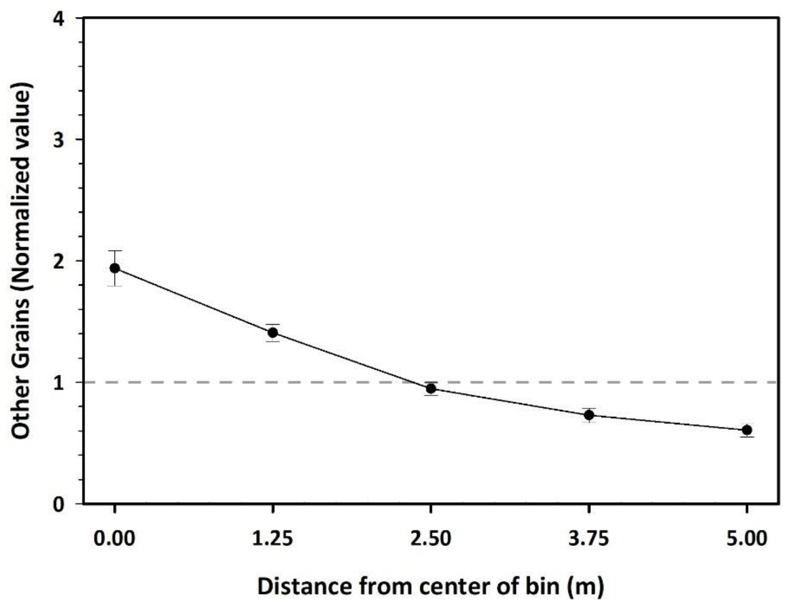

Fig. 4.2. The normalized value of other grains at different horizontal distances from center of bin. Dashed line shows the normalized value (1.0) of the average.

4.3.3. Other particles

Drop height did not have a significant effect on the distribution of other particles in the bin (Table 4.8). This is opposite to Parker et al. (2005). This contradiction could be due to the lower percentage of other particles in this study. The percentage of other particles changed parabolically by changing horizontal distance from center of bin with largest amount being near the wall (Table 4.8). Other particles in the bin were mostly concentrated in the center and periphery of the bin and were less found in the mid locations of the bin (Table 4.9, Fig. 4.3). The percentage of other particles decreased from 0.140 ± 0.019% in the center to 0.047 ± 0.005% in the mid location and then increased to the maximum amount of 0.184 ± 0.011% close to the wall. Other particles were accumulated roughly 1.8 times the average value near the wall of the bin (Fig. 4.3).

Table 4.8. Effect of drop height and horizontal distance from center of bin on the distribution of other particles (two-way ANOVA).

Source of Variation	DF	F	P-value
Height	4	2.406	0.054
Distance	4	287.974	<0.001
Height × Distance	16	6.495	<0.001

Table 4.9. Pairwise comparison (Tukey test) of the percentage of other particles at different horizontal distances from center of bin.

Horizontal distance from the center (m)	Other particles (%)
0.00	0.140 ± 0.019 a
1.25	0.067 ± 0.006 b
2.50	0.047 ± 0.005 b
3.75	0.116 ± 0.006 a
5.00	0.184 ± 0.011 c

Means with the same letter are not significantly different from each other (P<0.05)

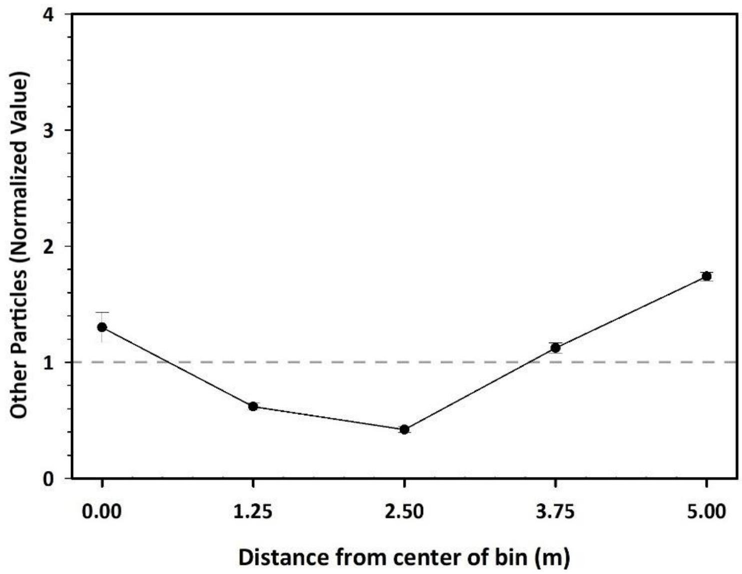

Fig. 4.3. The normalized value of other particles at different horizontal distances from center of bin. Dashed line shows the normalized value (1.0) of the average.

4.3.4. Shrunken and broken kernels

Shrunken and broken kernels (SBK) are actually unsound wheat kernels that have less quality than sound wheat kernels. Drop height did not have a significant effect on the distribution of SBK in the bin (Table 4.10). The percentage of SBK did not change significantly with increasing horizontal distance from center of bin except near the wall where it increased (Tables 4.11, Fig. 4.4). Most SBK were found near the wall of bin (Table 4.11). This is opposite to the results reported by Nourmohamadi-Moghadami et al. (2020) that broken kernels including fines in bulk corn were concentrated in the center of bin during loading. This contradiction could be due to the big difference in physical properties of wheat and corn or because that the fine particles were included in corn broken kernels in Nourmohamadi-Moghadami et al. (2020) study. Besides, SBK separated from wheat in this study contained a small portion of canola that might affect the results because canola kernels in a wheat mixture tend to bounce to the periphery of the bin during loading (Narendran et al. 2019).

Table 4.10. Effect of drop height and horizontal distance from center of bin on the distribution of shrunken and broken kernels (two-way ANOVA).

Source of Variation	DF	F	P-value
Height	4	0.101	0.982
Distance	4	71.913	<0.001
Height × Distance	16	2.583	0.002

Table 4.11. Pairwise comparison (Tukey test) of the percentage of shrunken and broken kernels at different horizontal distances from center of bin.

Horizontal distance from the center (m)	Shrunken and broken kernels (%)
0.00	0.190 ± 0.011 a
1.25	0.162 ± 0.005 a
2.50	0.147 ± 0.005 a
3.75	0.164 ± 0.009 a
5.00	0.240 ± 0.013 c

Means with the same letter are not significantly different from each other (P<0.05)

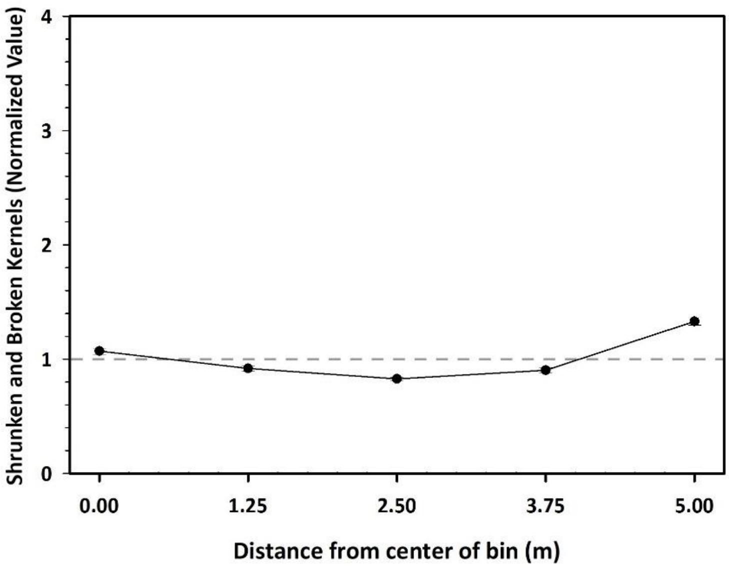

Fig. 4.4. The normalized value of shrunken and broken kernels at different horizontal distances from center of bin. Dashed line shows the normalized value (1.0) of the average.

4.3.5. Fine particles

Fine particles comprised the most portion of DFM in wheat. Drop height and horizontal distance from the center of bin had significantly influenced the radial distribution of fine particles in the bin (Table 4.12). Table 4.13 shows the radial distribution of fine particles in the bin for different drop heights. For all drop heights fine particles were negatively correlated to the horizontal distance from the center of bin (Table 4.13). These were highly concentrated in the center of bin and less found in the periphery (Fig .4.5). This result agrees with previous studies (Chang et al. 1986; Parker et al. 2005). The reason behind the accumulation of fine particles in the center of bin is that the sifting mechanism is dominant for fine particles, therefore, fine particles percolate between larger particles in the center before they reach the outer locations of the bin (Tang and Puri 2004). However, Jayas et al. (1987) reported that there was no significant difference in the concentration of fine particles in canola mixture in different locations of the bin.

Figure 4.5 indicates that uniformity of fine particles between center of bin and other location increased by increasing drop height to above 4.3 m. This agrees with Drahun and Bridgwater (1983) that reported for fine particles larger than 250 μm, uniformity increased with increasing free-fall height, and also Narendran et al. (2019) that observed loading height significantly influenced the distribution of canola kernels in wheat mixture. Fine particles accumulated about 3.5 to 4 times of the average value in the center of bin in 1.6 m and 3.4 m drop height, and dramatically reduced to the average value at 1.25 m distance from the center (Fig. 4.5, Table 4.13). The concentration of fine particles in the center of bin for other drop heights was approximately two times of the average value. There were no significant changes found for the percentage of fine particles at mid locations of the bin moving toward the wall (Table 4.13).

Table 4.12. Effect of drop height and horizontal distance from center of bin on the distribution of fine particles (two-way ANOVA).

Source of Variation	DF	F	P-value
Height	4	10.954	<0.001
Distance	4	451.085	<0.001
Height × Distance	16	19.399	<0.001

Table 4.13. Pairwise comparison (Tukey test) of the percentage of fine particles at different locations (horizontal distances from the center) for each drop height. r is the correlation coefficient.

Horizontal distance from the center (m)	Drop Height (m)				
	5.2	**4.3**	**3.4**	**2.5**	**1.6**
0.00	0.347 ± 0.021 a	0.361 ± 0.021 a	0.684 ± 0.021 a	0.338 ± 0.021 a	1.002 ± 0.021 a
1.25	0.172 ± 0.012 b	0.232 ± 0.012 b	0.179 ± 0.012 b	0.180 ± 0.012 b	0.263 ± 0.012 b
2.50	0.136 ± 0.012 bc	0.135 ± 0.012 c	0.123 ± 0.012 c	0.145 ± 0.012 bc	0.198 ± 0.012 c
3.75	0.117 ± 0.012 c	0.092 ± 0.012 c	0.117 ± 0.012 c	0.122 ± 0.012 c	0.164 ± 0.012 c
5.00	0.103 ± 0.012 c	0.099 ± 0.012 c	0.103 ± 0.012 c	0.101 ± 0.012 c	0.249 ± 0.012 b
r	-0.787	-0.852	-0.652	-0.821	-0.541
P-value	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter in each column associated with one drop height are not significantly different from each other (P<0.05).

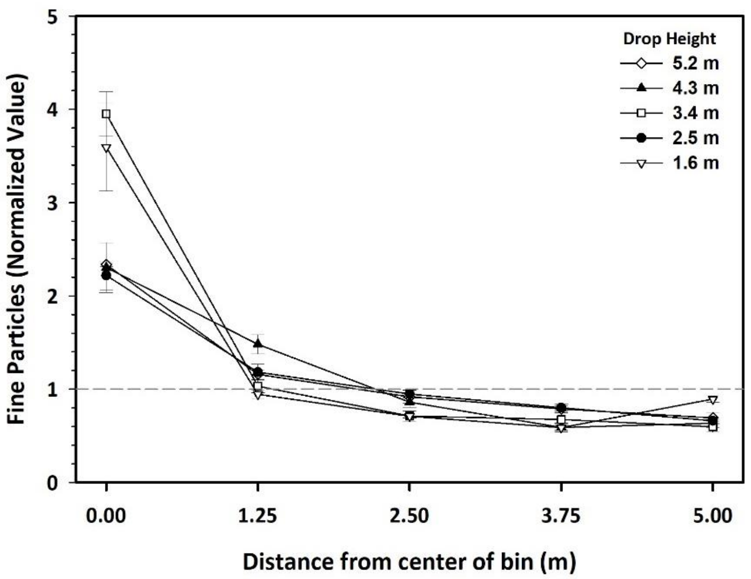

Fig. 4.5. The normalized value of fine particles at different horizontal distances from center of bin for different drop heights. Dashed line shows the normalized value (1.0) of the average.

4.3.6. Dust and fragments

Dust and fragments with dimensions smaller than 0.30 mm are the tiniest particles of DFM in wheat and they followed roughly the same radial distribution trend as of fine particles. Drop height and horizontal distance from the center of bin had significantly influenced the radial distribution of dust and fragments in the bin (Table 4.14). Table 4.15 shows the radial distribution of fine particles in the bin for different drop heights. For all drop heights, dust and fragments had a negative correlation with the distance from the center of bin (Table 4.15). These were highly concentrated in the center of bin and were found less in the periphery (Fig. 4.6) which agrees with previous studies (Chang et al. 1986; Tang and Puri 2004). The reason for the accumulation of tiny fragments including dust in the center of bin is the same as fine particles and is caused by the dominance of the sifting mechanism (Tang and Puri 2004). However, the distribution of dust particles smaller than 0.10 mm was reported to be different because these particles could be mainly influenced by the air current and tend to settle in the periphery of the bin near the wall (Jian et al. 2019; Theimer 1973).

Figure 4.6 shows that by increasing drop height to above 4.3 m, uniformity of dust and fragments between center of bin and other location increased. This agrees with Drahun and Bridgwater (1983) that reported uniformity of particles larger than 250 μm increased with increasing free-fall height. Accumulation of dust and fragments in the center of bin for 1.6 m and 3.4 m drop height was more serious compared to other drop heights (Fig. 4.6). For these drop heights, dust and fragments accumulated approximately seven times of the average value in the center of bin, and then nosedived to the average value at 1.25 m distance from the center. The concentration of dust and fragments in the center of bin for other drop heights was approximately 4 to 5 times of the average value. No significant changing trends were found for the distribution of fine particles at mid locations of the bin moving toward the wall (Table 4.15).

Table 4.14. Effect of drop height and horizontal distance from center of bin on the distribution of dust and fragments (two-way ANOVA).

Source of Variation	DF	F	P-value
Height	4	10.501	<0.001
Distance	4	670.864	<0.001
Height × Distance	16	15.984	<0.001

Table 4.15. Pairwise comparison (Tukey test) of the percentage of dust and fragments at different locations (horizontal distances from the center) for each drop height. r is the correlation coefficient.

Horizontal distance from the center (m)	Drop Height (m)				
	5.2	**4.3**	**3.4**	**2.5**	**1.6**
0.00	0.112 ± 0.009 a	0.118 ± 0.009 a	0.518 ± 0.009 a	0.208 ± 0.009 a	0.665 ± 0.009 a
1.25	0.038 ± 0.005 b	0.044 ± 0.005 b	0.083± 0.005 b	0.068 ± 0.005 b	0.085 ± 0.005 b
2.50	0.020 ± 0.005 bc	0.022 ± 0.005 c	0.029 ± 0.005 c	0.023 ± 0.005 c	0.055 ± 0.005 c
3.75	0.013 ± 0.005 c	0.013 ± 0.005 c	0.021 ± 0.005 c	0.013 ± 0.005 c	0.029 ± 0.005 d
5.00	0.015 ± 0.005 c	0.013 ± 0.005 c	0.022 ± 0.005 c	0.015 ± 0.005 c	0.032 ± 0.005 d
r	-0.734	-0.792	-0.648	-0.730	-0.623
P-value	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter in each column associated with one drop height are not significantly different from each other (P<0.05).

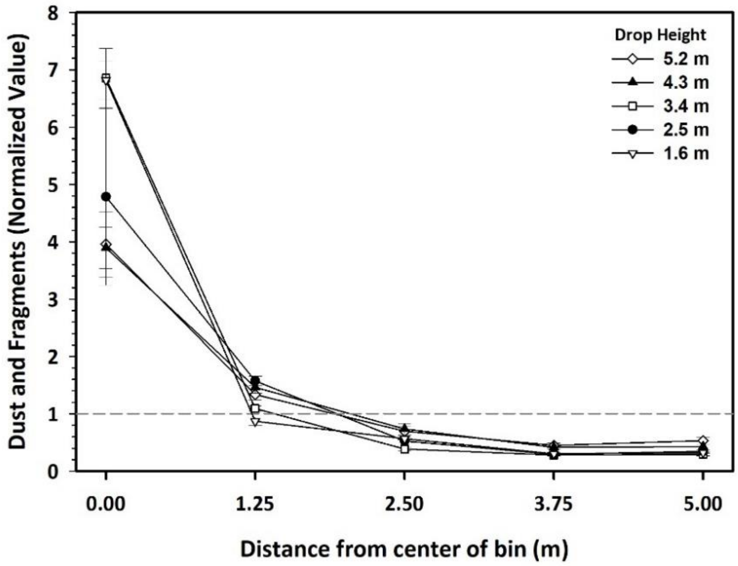

Fig. 4.6. The normalized value of dust and fragments at different horizontal distances from center of bin for different drop heights. Dashed line shows the normalized value (1.0) of the average.

4.4. Small and large wheat kernels distribution

4.4.1. Percentage of small and large wheat kernels in clean wheat

The percentage of small wheat kernels (≤ 2.80 mm) slightly decreased and of large wheat kernels (> 2.80 mm) slightly increased with increasing horizontal distance from the center of bin, while drop height did not have a significant effect on their distribution (Table 4.16). The average percentage of large wheat kernels was about three times the average percentage of small wheat kernels in clean wheat samples (Table 4.17 and Fig. 4.7). No other study was found in literature.

Table 4.16. Effect of drop height and horizontal distance from center of bin on the percentage of small wheat kernels and large wheat kernels in clean wheat (two-way ANOVA).

Wheat	Source of Variation	DF	F	P-value
Small Wheat Kernels	**Height**	4	0.134	0.969
	Distance	4	4.371	0.003
	Height × Distance	16	0.376	0.985
Large Wheat Kernels	**Height**	4	0.134	0.969
	Distance	4	4.380	0.003
	Height × Distance	16	0.377	0.985

Table 4.17. Pairwise comparison (ANOVA, Tukey test) of the percentage of small wheat kernels and large wheat kernels in clean wheat at different horizontal distances from the center of bin.

Horizontal distance from center of bin (m)	Small Wheat Kernels	Large Wheat Kernels
0.00	25.6 ± 0.7 a	74.4 ± 0.7 a
1.25	25.8 ± 0.4 a	74.2 ± 0.4 a
2.50	23.9 ± 0.4 b	76.1 ± 0.4 b
3.75	24.8 ± 0.4 ab	75.2 ± 0.4 ab
5.00	23.7 ± 0.4 b	76.3 ± 0.4 b
Average	24.6 ± 0.2 x	75.4 ± 0.2 y

Means with the same letter in each column are not significantly different from each other (P<0.05)
Means with the same letter in the average row are not significantly different from each other (P<0.05)

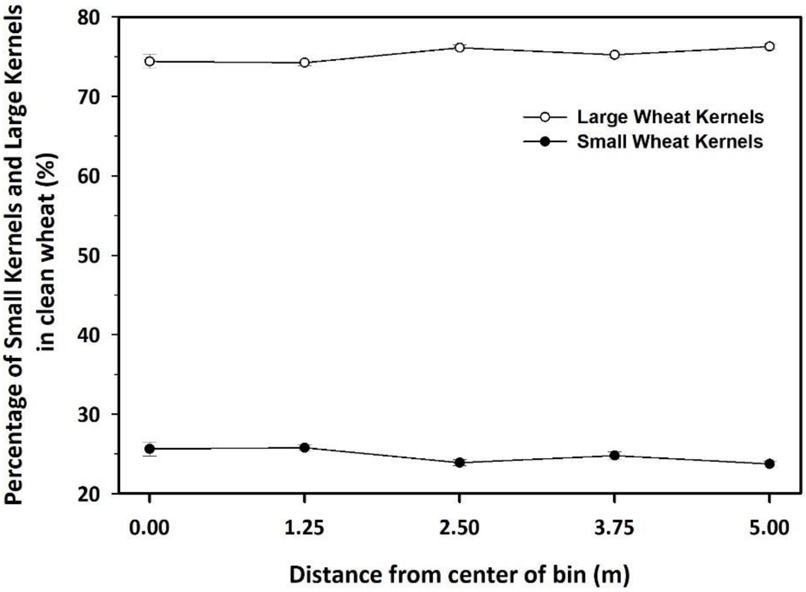

Fig. 4.7. Percentage of small and large wheat kernels in clean wheat at different horizontal distances from center of bin.

4.4.2. Test weight (bulk density) of small and large clean wheat kernels

Test weight of small clean wheat kernels was significantly lower than test weight of large clean wheat kernels (Table 4.19). This agrees with Dexter and D'Egidio (2012) that reported the test weight of durum wheat retained in different-size sieves decreased when the size of sieve's apertures decreased, i.e., when the portion of smaller kernels was higher in durum wheat, the test weight was lower. This is because small kernels have more intergranular void spaces between the kernels compare to large kernels. Drop height did not have a significant effect on the test weight of small and large wheat kernels in the bin. No significant differences were found between small kernel test weight at different locations of the bin, while there was a slight difference between mid-locations and other locations of the bin for large kernel test weight. No significant increasing or decreasing trend was observed for small or large kernel test weight along a radius of the bin.

Table 4.18. Effect of drop height and horizontal distance from center of bin on the test weight of clean small wheat kernels and clean large wheat kernels (two-way ANOVA).

Wheat	Source of Variation	DF	F	P-value
Small	**Height**	4	0.127	0.972
Wheat	**Distance**	4	1.715	0.152
Kernels	**Height × Distance**	16	1.161	0.312
Large	**Height**	4	0.306	0.874
Wheat	**Distance**	4	6.270	<0.001
Kernels	**Height × Distance**	16	2.182	0.100

Table 4.19. Pairwise comparison (ANOVA, Tukey test) of test weight of small wheat kernels and large wheat kernels in clean wheat at different horizontal distances from the center of bin.

Horizontal distance from center of bin (m)	Small Wheat Kernels	Large Wheat Kernels
0.00	822.7 ± 0.8 a	836.1 ± 0.6 a
1.25	824.3 ± 0.5 a	835.8 ± 0.4 a
2.50	824.1 ± 0.5 a	838.1 ± 0.4 b
3.75	824.4 ± 0.5 a	837.4 ± 0.4 b
5.00	823.1 ± 0.5 a	836.4 ± 0.4 a
Average	823.9 ± 0.3 x	836.9 ± 0.3 y

Means with the same letter in each column are not significantly different from each other (P<0.05)
Means with the same letter in the average row are not significantly different from each other (P<0.05)

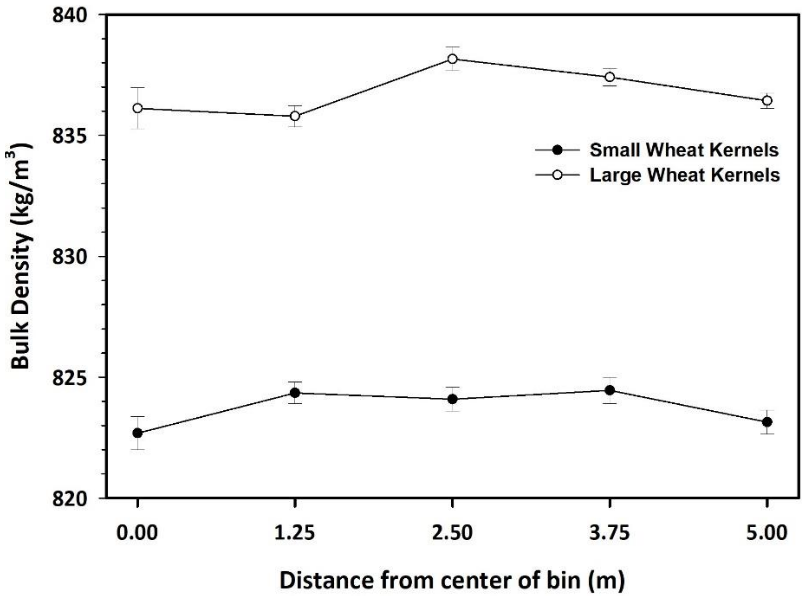

Fig. 4.8. Bulk density (test weight) of small and large clean wheat kernels at different horizontal distances from center of bin.

4.5. Test weight (bulk density), true density, and porosity of DFM and SBK

Bulk density, true density, and porosity of all different groups of impurities removed from wheat were significantly different from each other (Table 4.20). Bulk density of all groups was significantly lower than bulk density (test weight) of clean and unclean wheat. This agrees with previous studies that reported bulk density of mixture decreased by increasing the percentage of other grain (Narendran et al. 2019), chaff (Bian et al. 2015), and fine particles (Jayas et al. 1989). True density of all groups of impurities except dust and fragments was also lower than the true density of clean and unclean wheat kernels. Maximum true density was 1512.7 ± 2.5 kg/m^3 for dust and fragments which is similar to 1483.2 – 1487.8 kg/m^3 at 12 - 14% MC (w.b.) for dust removed from wheat (Bian et al. 2015a). Porosity of all groups of impurities except other grains was significantly higher than the porosity of clean and unclean wheat. The porosity of other particles, fine particles, and dust and fragments were 80.8 ± 0.2%, 79.0 ± 0.2% and 62.8 ± 0.2%, respectively which is much higher than the porosity of wheat kernels. However, because the percentage of these particles in wheat was low, the presence of them did not affect the porosity of unclean wheat compared to clean wheat.

Table 4.20. Bulk density, true density, and porosity of impurities removed from CWRW wheat.

Impurities	Bulk Density (kg/m^3)	True Density (kg/m^3)	Porosity (%)
Other grains	746.7 ± 2.2 a	1248.4 ± 2.6 a	40.2 ± 0.3 a
Other particles	234.4 ± 2.0 b	1221.8 ± 2.9 b	80.8 ± 0.2 b
Shrunken and broken kernels	775.2 ± 3.0 c	1402.9 ± 2.3 c	44.7 ± 0.3 c
Fine particles	273.5 ± 2.0 d	1304.3 ± 2.5 d	79.0 ± 0.2 d
Dust and fragments	562.9 ± 2.7 e	1512.7 ± 2.5 e	62.8 ± 0.2 e
Unclean wheat	829.2 ± 0.4 f	1430.1 ± 0.3 f	42.0 ± 0.1 f
Clean wheat	833.7 ± 0.3 g	1439.4 ± 0.3 g	42.0 ± 0.1 f

Means with the same letter in each column are not significantly different from each other ($P<0.05$)

4.6. True density of clean and unclean wheat

True density of clean wheat (after removing impurities) was significantly higher than the true density of unclean wheat. The average true density of clean wheat and unclean wheat was 1439.4 ± 0.3 kg/m^3 and 1430.1 ± 0.3 kg/m^3, respectively (Table 4.22) which was higher than the range of 1379 – 1390 kg/m^3 reported by Muir and Sinha (1988) for three varieties of hard red spring wheat at 12.7% MC grown in western Canada (no report of the percentage of DFM). It was also higher than the range of 1377 – 1410 kg/m^3 reported for durum wheat at 12.7% MC grown in western Canada (no report of the percentage of DFM) (Muir and Sinha 1988). The difference between the true density of clean and unclean wheat implies that the true density of total impurities removed from wheat must be lower than the true density of wheat kernels (Table 4.10).

Drop height did not have a significant effect on the true density of clean and unclean wheat kernels. Besides, no significant differences were found for the true density of clean wheat by changing the horizontal distance of the sampling location from the center of bin. However, the true density of unclean wheat collected from 1.25 m distance from the center of bin was slightly higher than the locations near the wall of the bin (Table 4.22). No regularly increasing or decreasing trend was found for changing the true density of unclean wheat by changing the horizontal distance from the center of bin.

Table 4.21. Effect of drop height and horizontal distance from center of bin on the true density of clean wheat and unclean wheat (two-way ANOVA).

Wheat	Source of Variation	DF	F	P-value
Clean Wheat	**Height**	4	0.115	0.977
	Distance	4	0.359	0.837
	Height × Distance	16	1.420	0.146
Unclean Wheat	**Height**	4	0.322	0.862
	Distance	4	4.455	0.002
	Height × Distance	16	2.869	<0.001

Table 4.22. Pairwise comparison (Tukey test) of true density of clean wheat and unclean wheat at different horizontal distances from the center of bin.

Horizontal distance from center of bin (m)	Clean wheat	Unclean wheat
0.00	1439.2 ± 1.1 [a]	1430.3 ± 0.8 [ab]
1.25	1439.1 ± 0.6 [a]	1431.4 ± 0.4 [a]
2.50	1440.0 ± 0.6 [a]	1430.1 ± 0.4 [ab]
3.75	1439.1 ± 0.6 [a]	1430.0 ± 0.4 [ab]
5.00	1439.6 ± 0.6 [a]	1428.8 ± 0.4 [b]
Average	1439.4 ± 0.3 [x]	1430.1 ± 0.3 [y]

Means with the same letter in each column are not significantly different from each other (P<0.05)
Means with the same letter in the average row are not significantly different from each other (P<0.05)

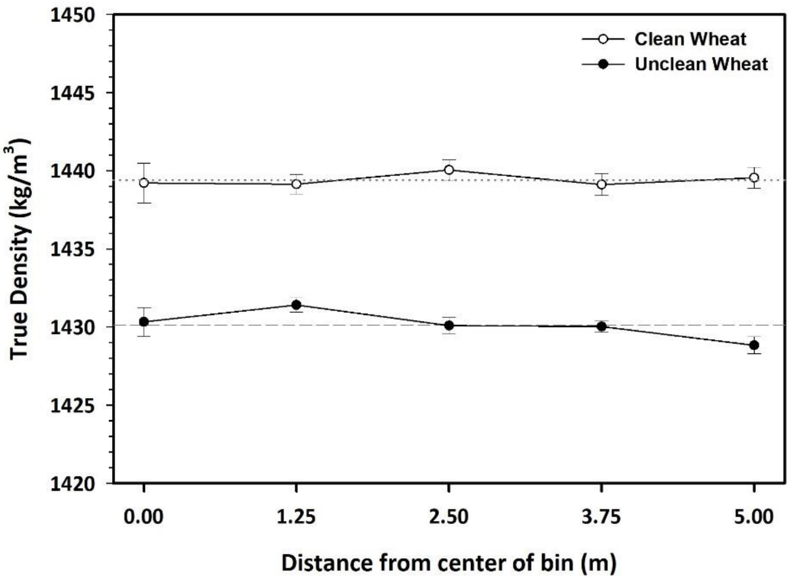

Fig. 4.9. Clean wheat and unclean wheat true density at different horizontal distances from center of bin. Dashed line and dotted line show the average true density of unclean wheat and clean wheat, respectively.

4.7. Test weight (bulk density) of clean and unclean wheat

The test weight of clean wheat (833.7 ± 0.3 kg/m^3) was significantly higher than the test weight of unclean wheat (829.2 ± 0.4 kg/m^3) (Table 4.24). The reason is that the bulk density (test weight) of impurities was significantly lower than the test weight of wheat kernels (Table 4.20). This result agrees with Bian et al. (2015) who reported the bulk density of wheat mixture reduced by increasing the percentage of chaff and also agrees with Jayas et al. (1989) who reported by increasing the percentage of either chaff or fines, the bulk density of canola mixture decreased. Another reason behind the difference between test weight of clean and unclean wheat is that the true density of impurities removed from wheat (except dust and fragments) was lower than the true density of wheat kernels. So, when bulk wheat contains impurities (larger than dust and fragments) especially large impurities (larger than wheat kernels), these impurities substitute wheat kernels in a unit volume of bulk wheat and due to a lower true density, decrease the test weight of unclean wheat. However, because the percentage of total impurities in grade two CWRW wheat was low, the presence of them did not noticeably affect the test weight of unclean wheat compare to clean wheat. The average test weight of clean wheat was 833.7 ± 0.3 kg/m^3. For unclean wheat, the average test weight was 829.2 ± 0.4 kg/m^3 which was higher than the minimum 740 kg/m^3 (370 g/0.5 L) assigned for grade two CWRW wheat by Canadian Grain Commission. The measured test weight of both clean and unclean wheat was higher than the range of 763 - 780 kg/m^3 reported by Muir and Shina (1988) for three varieties of hard red spring wheat at 12.7% MC, grown in western Canada (no report of the percentage of DFM). The measured test weight was also higher than the range of 744 - 794 kg/m^3 reported for two varieties of durum wheat at 12.7% MC, grown in western Canada (no report of the percentage of DFM) (Muir and Sinha 1988).

Bulk density of collected samples was measured in laboratory using a test weight apparatus. This measured test weight might be different from bulk density that can be measured inside the bin (in-situ bulk density) without disturbing the grain. Therefore, any differences that were observed between test weights of collected samples were due to the differences in the percentage of segregated particles, not due to compaction caused by drop height. Drop height did not have a significant effect on the test weight of clean and unclean wheat kernels (Table 4.23). Test weight of clean wheat in the center location, 1.25 m away from the center, and near the wall of the bin was similar but significantly lower than the test weight of clean wheat in the mid locations (Table 4.24). No regular increasing or decreasing trend for clean wheat test weight with radius was found. This could be because the percentage of large wheat kernels that have a significantly higher test weight compared to the clean wheat (Table 4.19), is higher in mid locations of the bin (Table 4.17). Test weight of clean wheat in the inner part of the bin was below the average value, while in the mid locations of the bin it was higher than the average, and near the wall of the bin, it was approximately about the average (Fig. 4.10). For unclean wheat, test weight increased from 826.0 ± 0.7 kg/m^3 in the center to 832.0 826.0 ± 0.4 kg/m^3 in 3.75 distance from the center but suddenly decreased to the same level of the center in locations near the wall of the bin (Table 4.24). Narendran et al. (2018) also reported that the test weight of wheat mixed with soybean, kidney bean, and canola was lowest in the periphery of the bin. While in mid locations of the bin, test weight of unclean wheat was higher than the average value, in the center and near the wall of the bin, it was found to be lower than the average value (Fig. 4.10). Test weight of unclean wheat approximately followed the same trend as the test weight of clean wheat by moving from the center of bin toward the periphery (Fig. 4.10). This could be interpreted that the test weight of unclean wheat is mostly related to the test weight of wheat kernels and this is true because wheat kernels comprise the vast majority of particles in the grain mixture. Furthermore, large, small, and therefore total impurities were more accumulated in the central locations and near the wall of the bin. As removed impurities had a lower true density compared to wheat kernels (Table 4.20), the accumulation of these particles in the center and near the wall of the bin decreased the test weight of the mixture associated with those locations.

Table 4.23. Effect of drop height and horizontal distance from center of bin on the test weight (bulk density) of clean wheat and unclean wheat (two-way ANOVA).

Wheat	Source of Variation	DF	F	P-value
Clean Wheat	**Height**	4	0.263	0.901
	Distance	4	8.872	<0.001
	Height × Distance	16	4.186	<0.001
Unclean Wheat	**Height**	4	0.086	0.987
	Distance	4	42.577	<0.001
	Height × Distance	16	2.526	0.003

Table 4.24. Pairwise comparison (Tukey test) of test weight (bulk density) of clean wheat and unclean wheat at different horizontal distances from the center of bin.

Horizontal distance from center of bin (m)	Clean wheat	Unclean wheat
0.00	832.7 ± 0.6 a	826.0 ± 0.7 a
1.25	832.5 ± 0.3 a	828.6 ± 0.4 b
2.50	834.8 ± 0.3 b	831.6 ± 0.4 c
3.75	834.6 ± 0.3 b	832.1 ± 0.4 c
5.00	833.4 ± 0.3 ab	825.4 ± 0.4 a
Average	833.7 ± 0.3 x	829.2 ± 0.4 y

Means with the same letter in each column are not significantly different from each other (P<0.05)
Means with the same letter in the average row are not significantly different from each other (P<0.05)

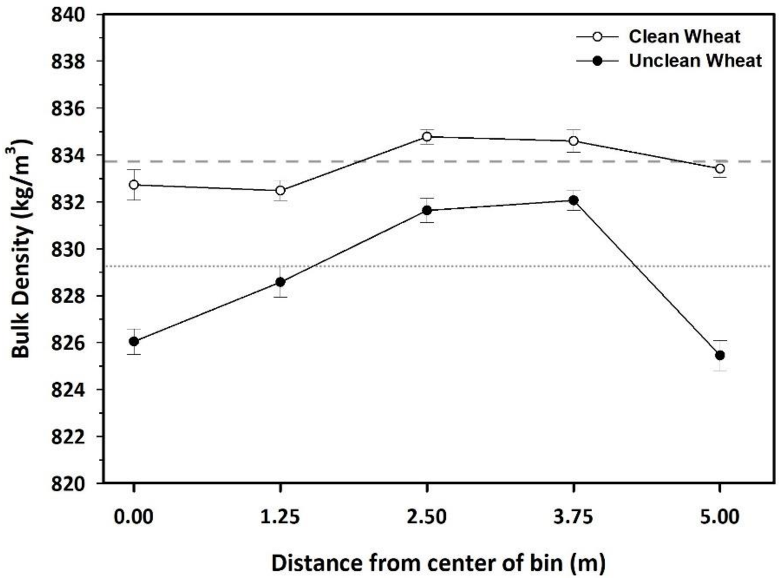

Fig. 4.10. Clean wheat and unclean wheat test weight (bulk density) at different horizontal distances from center of bin. Dashed line and dotted line show the average bulk density of clean wheat and unclean wheat, respectively.

4.8. Porosity of clean and unclean wheat

No significant difference was found between the porosity of clean wheat and unclean wheat. This means that based on the relationship between porosity, bulk density (test weight), and true density (Equation 3.3), bulk density and true density increased at the same rate by removing impurities from wheat so that porosity did not change. In addition, porosity of clean and unclean wheat was constant along the radius of the bin, and no increasing or decreasing trend was found for the changes of porosity by changing the distance from the center of bin. This is contradictory to Jayas et al. (1989) who reported that by increasing the percentage of chaff and fines, porosity increased linearly. The reason could be due to the small amount of impurities (especially DFM) in grade two CWRW wheat. Although the porosity of impurities (except other grains) was higher than the porosity of wheat kernels (Table 4.20), due to the low percentage of impurities in wheat, changes in porosity due to segregation was negligible. The porosity of wheat (clean or unclean) was 42.0 ± 0.1% which is a little higher than the range of 38 – 39% reported by Muir and Shina (1988) for three varieties of hard red spring wheat with 12.7% MC grown in western Canada (no report of the percentage of DFM). It was also higher than the range of 38 – 41% reported for two varieties of durum wheat with 12.7% MC grown in western Canada (no report of the percentage of DFM) (Muir and Sinha 1988).

Since the percentage of impurities (DFM and SBK) in wheat was low, no significant change would be expected in the equivalent particle diameter (d_e) of particles in the mixture (Equation 2.2). In addition, no significant changes were found in the porosity of unclean wheat in different locations along a radius of the bin. Therefore, based on Ergun's model for airflow resistance inside bulk grain (Equation 2.2), no noticeable increase in airflow resistance is expected in the center of bin.

Table 4.25. Effect of drop height and horizontal distance from center of bin on the porosity of clean wheat and unclean wheat (two-way ANOVA).

Wheat	Source of Variation	DF	F	P-value
Clean Wheat	**Height**	4	0.153	0.961
	Distance	4	1.843	0.126
	Height × Distance	16	1.373	0.248
Unclean Wheat	**Height**	4	0.089	0.985
	Distance	4	2.380	0.056
	Height × Distance	16	1.625	0.173

4.9. Thousand kernel weight (TKW)

No significant difference and therefore no increasing or decreasing trend was found for the change of TKW along the radius of the bin or for different drop heights (Table 4.26). The TKW of wheat was 34.945 ± 0.606 g. This is higher than 33.870 g and 32.238 g reported as TKW of green wheat and five different varieties of bread wheat (at the same moisture content of this study), respectively (Al-Mahasneh and Rababah 2007; Tabatabaeefar 2003), but much lower than the range of 42.5 – 55.5 g reported for nine durum wheat genotypes (El-Khayat et al. 2006). Although the percentage of large wheat kernels was slightly higher in the mid locations and locations close to the wall of the bin (table 4.17), however the difference between the percentage of large wheat kernels was not high enough to result in any difference in TKW.

Table 4.26. Effect of drop height and horizontal distance from center of bin on thousand kernel weight of wheat (two-way ANOVA).

Source of Variation	DF	F	P-value
Height	4	0.636 ns	0.637
Distance	4	1.778 ns	0.138
Height × Distance	16	1.923 ns	0.112

4.10. Wheat kernel dimensions

No significant differences were found in the length, width, and thickness of wheat kernels at different radial locations of the bin or for different drop heights (Table 4.27). The length, width, and thickness were 6.10 ± 0.39 mm, 3.01 ± 0.16 mm, and 2.77 ± 0.14 mm, respectively. These dimensions were lower than what reported by Tabatabaeefar (2003) for five varieties of bread wheat (7.08, 3.27, and 2.98 mm for length, width, and thickness, respectively).

Table 4.27. Effect of drop height and horizontal distance from center of bin on the dimensions of wheat kernels (two-way ANOVA).

Dimension	Source of Variation	DF	F	P-value
Length	**Height**	4	0.076	0.989
	Distance	4	1.375	0.248
	Height × Distance	16	1.021	0.441
Width	**Height**	4	0.199	0.938
	Distance	4	0.371	0.829
	Height × Distance	16	1.014	0.448
Thickness	**Height**	4	0.053	0.995
	Distance	4	0.550	0.699
	Height × Distance	16	0.555	0.910

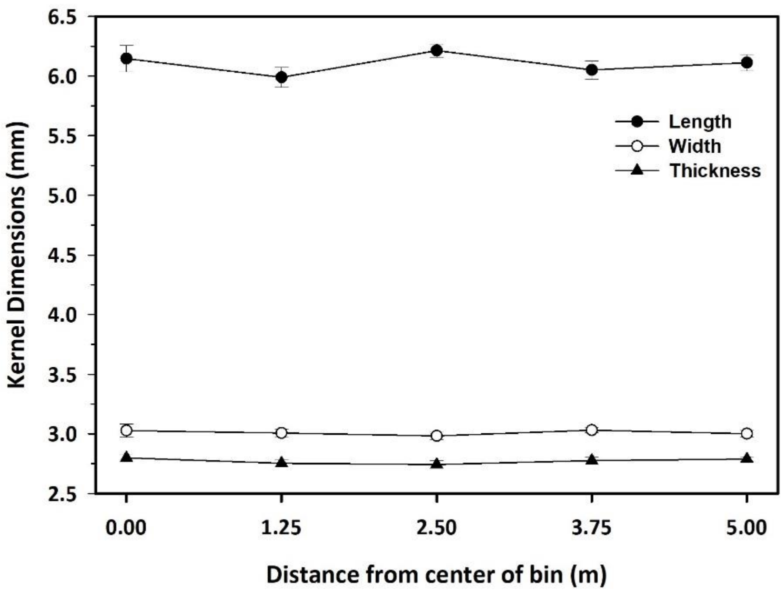

Fig. 4.11. Wheat kernel dimensions at different horizontal distances from center of bin.

4.11. Wheat kernel sphericity

No significant changes were found in the sphericity of wheat kernels for different drop heights or at different locations along the radius of the bin (Table 4.28). The average sphericity of wheat kernels was 0.608 ± 0.033. This is similar to sphericity reported for different varieties of bread wheat (Kalkan and Kara 2011; Tabatabaeefar 2003).

Table 4.28. Effect of drop height and horizontal distance from center of bin on the sphericity of wheat kernels (two-way ANOVA).

Source of Variation	DF	F	P-value
Height	4	0.058	0.994
Distance	4	1.514	0.204
Height × Distance	16	0.809	0.672

5. CONCLUSIONS

This study has led to the following conclusions for grade two CWRW wheat with maximum measured percentage of total impurities (including dockage, foreign materials, and shrunken and broken kernels) of 0.804 ± 0.084% by weight at 12.2 ± 0.4% moisture content (w.b.):

1. The average in-situ filling angle of repose for five different drop heights (1.6 m to 5.2 m) was 22.9 ± 1.4°.
2. Drop height significantly affected the radial distribution of impurities (total and small impurities) in the bin, however, no regularly increasing or decreasing trend was found.
3. Impurities smaller than wheat kernels were highly accumulated in the center of bin.
4. The uniformity of particles smaller than 1.7 mm (fine particles, and dust and fragments) between center and other locations of bin increased by increasing drop height to above 4.3 m.
5. Impurities larger than wheat kernels were found less in the mid locations of the bin.
6. Fine particles and dust and fragments (< 1.7 mm) comprised the majority of DFM in wheat and highly accumulated in the center of bin.
7. Stones were only found in the center of bin; but seldom.
8. Other large grains (Corn and soybean) in grade two CWRW were found more in the center of bin.
9. Other particles in the bin were less found in the mid locations of the bin.
10. Shrunken and broken kernels (SBK) were found mostly near the wall of the bin.
11. True density and test weight (bulk density) of clean wheat was higher than unclean wheat.
12. Drop height did not influence the true density and test weight (bulk density) of clean and unclean wheat.

13. No significant changes in porosity, thousand kernel weight, kernel dimension, and sphericity were found along the radius of the bin or for different drop heights.

6. LIMITATION OF THIS STUDY

There were some limitations for this study that prevent generalizing the results for all wheat species during loading into bin. These limitations were:

1. The size variation of the DFM found in used bulk wheat did not cover all particles that can be found in bulk wheat.
2. The percentage of other cereals such as soybean and canola kernels were low.
3. Drop heights higher than the maximum drop height in this study (5.2 m) are common in commercial size bins, so this study could be done in a larger drop height range.
4. Bulk density of wheat in different locations of the bin was measured using test weigh of collected samples in laboratory. To consider the effect of compaction caused by different drop heights, bulk density of wheat in each location can be measured using a proper method in situation inside the bin (in-situ bulk density).
5. The in-situ filling angle of repose was measured only in the center of radii of the bin to avoid wheat heap disturbing. By using proper method for measuring angle of repose without disturbing the heap surface, angle of repose can be measured in more than one location along each radius of bin.

7. RECOMMENDATIONS FOR FUTURE RESEARCH

1. The effect of drop height, compaction and percentage of DFM on the in-situ filling angle of repose of wheat and other cereals loaded into farm bins needs to be studied in more details using a proper factorial experiment.
2. It is recommended to separate canola kernels from shrunken and broken kernels and then study the distribution of shrunken and broken kernels in bins.
3. It is recommended to separate dust smaller than 0.10 mm from other fragments of fine particles and then study the distribution of dust in bins.
4. The effect of density and shape of DFM seems to be important in the segregation of particles in bulk wheat and needs to be studied in detail.
5. A comprehensive study on the effect of flow rate during loading graded wheat into big size bins should be conducted.
6. Temperature varies a lot during a year in Canada. The effect of grain temperature on flowability and segregation of particles in bulk grain needs to be studied.

8. REFERENCES

Adam, B.D., P. Kenkel and K. Anderson. 1994. The economics of cleaning winter wheat for export : An evaluation of proposed federal " Clean Grain " standards. *Journal of Agricultural and Resource Economics* 19(2): 280–298.

Al-Mahasneh, M.A. and T.M. Rababah. 2007. Effect of moisture content on some physical properties of green wheat. *Journal of Food Engineering* 79(4): 1467–1473.

Arbogast, R.T., D.K. Weaver, P.E. Kendra and A.J. Brenner. 1998. Implications of Spatial Distribution of Insect Populations in Storage Ecosystems. *Pest Management and Sampling* 27: 202–216.

ASABE. 2017. ASAE S352.2 APR1988 (R2017). Moisture Measurement — Unground Grain and Seeds. *ASABE Standards*.

Athanassiou, C.G. and T.C. Buchelos. 2020. Grain properties and insect distribution trends in silos of wheat. *Journal of Stored Products Research* 88: 101632.

Baasandorj, T., J.B. Ohm, F. Manthey and S. Simsek. 2015. Effect of kernel size and mill type on protein, milling yield, and baking quality of hard red spring wheat. *Cereal Chemistry* 92(1): 81–87.

Bagster, D.F. 1996. Studies on the effect of moisture content and coarse and fine particle concentration on segregation in bins. *KONA Powder and Particle Journal* 14: 138–143.

Bates, L. 1997. *User Guide to Segregation*. London: British Materials Handling Board.

Beakawi Al-Hashemi, H.M. and O.S. Baghabra Al-Amoudi. 2018. A review on the angle of repose of granular materials. *Powder Technology* 330: 397–417.

Bhadra, R., K. Muthukumarappan and K.A. Rosentrater. 2009. Flowability properties of commercial distillers dried grains with solubles (DDGS). *Cereal Chemistry* 86(2): 170–180.

Bhadra, R., M.E. Casada, S.A. Thompson, J.M. Boac, R.G. Maghirang, M.D. Montross, A.P. Turner and S.G. McNeill. 2017. Field-observed angles of repose for stored grain in the United States. *Applied Engineering in Agriculture* 33(1): 131–137.

Bhople, S., A. Kumar and P. Haldkar. 2017. Effect of moisture content on angle of repose for different cereals and pulses. *International Journal of Chemical Studies* 5(5): 2283–2286.

Bian, Q., R.P.K. Ambrose and B. Subramanyan. 2015a. Effects of insect-infested kernels on bulk flow properties of wheat. *Journal of Stored Products Research* 63: 51–56.

Bian, Q., R.P.K. Ambrose and B. Subramanyam. 2015b. Effect of chaff on bulk flow properties of wheat. *Journal of Stored Products Research* 64: 21–26.

Brooker, D.B., F.W. Bakker-Arkema and C.W. Hall. 1992. *Drying and Storage of Grains and Oilseeds*. Springer Science & Business Media.

Van Burkalow, A. 1945. Angle of repose and angle of sliding friction: An experimental study. *Bulletin of the Geological Society of America* 56(6): 669–707.

Canadian Grain Commission. 2019. *Official Grain Grading Guide*. Canadian Grain Commission.

Canadian International Grains Institute. 2019. Wheat from Western Canada. Winnipeg.

Carson, J.W., T.A. Royal and D.J. Goodwill. 1986. Understanding and eliminating particle segregation problems. *Bulk Solids Handling* 6: 139–144.

Chang, C.S., L.E. Shackelford, F.S. Lai, C.R. Martin and B.S. Miller. 1981. Bulk properties of corn as affected by multiple-point grain spreaders. *American Society of Agricultural Engineers*.

Chang, C.S., H.H. Converse and C.R. Martin. 1983. Bulk properties of grain as affected by self-propelled rotational type grain spreaders. *Transactions of the ASAE* 80(3061).

Chang, C.S., H.H. Convers and F.S. Lai. 1986. Distribution of fines and bulk density of corn as affected by choke-flow, spout-flow, and drop-height. *Transactions of the ASAE* 29(2): 0618–0620.

Dexter, J.E. and M.G. D'Egidio. 2012. Grading Factors Impacting Durum Wheat Processing Quality. In *Durum Wheat: Chemistry and Technology*, 235–250. Elsevier Inc..

Drahun, J.A. and J. Bridgwater. 1983. The mechanisms of free surface segregation. *Powder Technology* 36: 39–53.

El-Khayat, G.H., J. Samaan, F.A. Manthey, M.P. Fuller and C.S. Brennan. 2006. Durum wheat quality I: Some physical and chemical characteristics of Syrian durum wheat genotypes. *International Journal of Food Science and Technology* 41: 22–29.

Fan, Y., K. V. Jacob, B. Freireich and R.M. Lueptow. 2017. Segregation of granular materials in bounded heap flow: A review. *Powder Technology* 312: 67–88.

FAO. 2018. Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/faostat (2020 /4/10)

Fiscus, D.E., G.H. Foster and K. Henry H. 1971. Physical damage of grain caused by various handling techniques. *Transactions of the ASAE* 14(3): 0480–0485.

Fu, J., C. Chen, J. Ferellec and J. Yang. 2020. Effect of particle shape on repose angle based on hopper flow test and discrete element method. *Advances in Civil Engineering*.

Gorial, B.Y. and J.R. O'Callaghan. 1990. Aerodynamic properties of grain/straw materials. *Journal of Agricultural Engineering Research* 46: 275–290.

Gornicki, K. and A. Kaleta. 2015a. Resistance of bulk grain to airflow – a review. Part I: Equations for airflow resistance. *Annals of Warsaw University of Life Sciences - SGGW* 65: 31–41.

Gornicki, K. and A. Kaleta. 2015b. Resistance of bulk grain to airflow - a review. Part II: Effect of process parameters. *Annals of Warsaw University of Life Sciences - SGGW* 65: 43–51.

Grama, S.N., C.J. Bern and C.R. Hurburgh. 1984. Airflow Resistance of Mixtures of Shelled Corn and Fines. *Transactions of the ASAE* 27(1): 268–272.

Hagstrum, D.W., T.W. Phillips and G. Cuperus. 2012. *Stored Product Protection*. Kansas State

University.

Hall, C. 1980. *Drying and Storage of Agricultural Crops*. Westport, Connecticut: AVI Publishing Company Inc..

Hall, G.E. 1974. Damage during handling of shelled corn and soybeans. *Transactions of the ASAE* 17(2): 0335–0338.

Hammami, F., S. Ben Mabrouk and A. Mami. 2016. Modelling and simulation of heat exchange and moisture content in a cereal storage silo. *Mathematical and Computer Modelling of Dynamical Systems* 22(3): 207–220.

Haque, E., G.H. Foster, D.S. Chung and F.S. Lai. 1978. Static pressure drop across a bed of corn mixed with fines. *Transactions of the ASAE* 21(5): 0997–1000.

Harein, P.K. 1961. Effect of dockage on the efficiency of 80 : 20 (Carbon Tetrachloride : Carbon Disulfide by Volume) as a fumigant for adult rice weevil, Sitophilus sasakii (Tak.) in wheat. *Journal of Kansas Entomological Society* 34(4): 195–197.

Harnby, N. 2000. An engineering view of pharmaceutical powder mixing. *Pharmaceutical Science and Technology Today* 3(9): 303–309.

Harwood, F. 1977. Powder segregation due to vibration. *Powder Technology* 16: 51–57.

Jain, A., M.J. Metzger and B.J. Glasser. 2013. Effect of particle size distribution on segregation in vibrated systems. *Powder Technology* 237: 543–553.

Jayas, D.S., S.S. Sokhansanj, E.B. Moysey and E.M. Barber. 1987. Distribution of foreign material in canola bins filled using a spreader or spout. *Canadian Agricultural Engineering* 29(2): 183–188.

Jayas, D.S. 1987. Resistance of bulk canola oilseed to airflow. University of Saskatchewan.

Jayas, D.S., S. Sokhansanj and N.D.G. White. 1989. Bulk density and porosity of two Canola species. *Transactions of the ASAE* 32(1): 291–294.

Jayas, D.S., N.D.G. White and M.G. Britton. 1992. Effect of oil used for dust control on engineering properties of stored wheat. *Transactions of the ASAE* 659–664.

Jayas, D.S., N.D.G. White and W.E. Muir. 1994. *Stored-Grain Ecosystems*. CRC Press.

Jayas, D.S. and S. Cenkowski. 2010. Grain property values and their measurement. In *Handbook of Industrial Drying*.

Jha, A.K., J.S. Gill and V.M. Puri. 2008. Percolation segregation in binary size mixtures of spherical and angular-shaped particles of different densities. *Particulate Science and Technology* 26(5): 482–493.

Jian, F., D.S. Jayas and N.D.G. White. 2005. Movement and distribution of adult Cryptolestes ferrugineus (Coleoptera : Laemophloeidae) in stored wheat in response to temperature gradients , dockage , and moisture differences. *Journal of Stored Products Research* 41: 401–422.

Jian, F., S. Yavari, R.B. Narendran and D.S. Jayas. 2018. Physical properties of Finola® hemp seeds: clean and containing dockages. *Applied Engineering in Agriculture* 34(6): 1017–

1026.

Jian, F., R.B. Narendran and D.S. Jayas. 2019. Segregation in stored grain bulks: Kinematics, dynamics, mechanisms, and minimization – A review. *Journal of Stored Products Research* 81: 11–21.

Johanson, J.R. 1996. Predicting segregation of bimodal particle mixtures using the flow properties of bulk solids. *Pharmaceutical Technology* 8(1): 38–44.

Johanson, K., C. Eckert, D. Ghose, M. Djomlija and M. Hubert. 2005. Quantitative measurement of particle segregation mechanisms. *Powder Technology* 159(1): 1–12.

Kalkan, F. and M. Kara. 2011. Handling, frictional and technological properties of wheat as affected by moisture content and cultivar. *Powder Technology* 213(1): 116–122.

Karimi, M., K. Kheiralipour, A. Tabatabaeefar, G.M. Khoubakht, M. Naderi and K. Heidarbeigi. 2009. The effect of moisture content on physical properties of wheat. *Pakistan Journal of Nutrition* 8(1): 90–95.

Kavallieratos, N.G., C.G. Athanassiou, F.D. Mpakou and A.E. Empassoukou. 2007. Factors affecting laboratory bioassays with diatomaceous earth on stored wheat: effect of insect density, grain quantity, and cracked kernel containment. *Journal of Economic Entomology* 1724–1731.

Ketterhagen, W.R., J.S. Curtis, C.R. Wassgren and B.C. Hancock. 2008. Modeling granular segregation in flow from quasi-three-dimensional, wedge-shaped hoppers. *Powder Technology* 179(3): 126–143.

Ketterhagen, W.R., J.S. Curtis, C.R. Wassgren and B.C. Hancock. 2009. Predicting the flow mode from hoppers using the discrete element method. *Powder Technology* 195(1): 1–10.

Koç, B., I. Eren and F. Kaymak Ertekin. 2008. Modelling bulk density, porosity and shrinkage of quince during drying: The effect of drying method. *Journal of Food Engineering* 85(3): 340–349.

Krumbein, W.C. 1941. Measurement and geological significance of shape and roundness of sedimentary particles. *Journal of Sedimentary Petrology* 11(2): 64–72.

Kumar, A. and W.E. Muir. 1986. Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. *Transactions of the ASAE* 29(5): 1423–1426.

Kurkuri, M.D., C. Randall and D. Losic. 2012. New method of measuring the angle of repose of hard wheat grain. In *Chemeca 2012: Quality of life through chemical engineering*, Wellington, New Zealand.

Lawrence, J. and D.E. Maier. 2011. Three-dimensional airflow distribution in a maize silo with peaked, levelled and cored grain mass configurations. *Biosystems Engineering* 110(3): 321–329.

Liao, C.C. 2018. A study of the effect of liquid viscosity on density-driven wet granular segregation in a rotating drum. *Powder Technology* 325: 632–638.

Liss, E.D., S.L. Conway, J.A. Zega and B.J. Glasser. 2004. Segregation of Powders during Gravity Flow through Vertical Pipes. *Pharmaceutical Technology* 28(2): 78–96.

Lumay, G., F. Boschini, K. Traina, S. Bontempi, J.C. Remy, R. Cloots and N. Vandewalle. 2012. Measuring the flowing properties of powders and grains. *Powder Technology* 224: 19–27.

Martin, C.R. and L.E. Stephens. 1977. Broken corn and dust generated during repeated handling. *Transactions of the ASAE*.

Mazhar, H., J. Bollmann, E. Forti, A. Praeger, T. Osswald and D. Negrut. 2014. Studying the effect of powder geometry on the selective laser sintering process. In *Annual Technical Conference - ANTEC*, 2171–2175.

McGlinchey, D. 1998. Assessment of segregation in industrial processes. Journal of Powder Bulk Solids Technology. *Journal of Powder Bulk Solids Technology* 22: 54–56.

Mcgregor, H.E. 1964. Preference of Tribolium castaneum for wheat containing various percentages of dockage. *Journal of Economic Entomology* 57(4): 511–513.

Mercier, A.S. 1989. Dockage and foreign material in the grading standards for wheat exports. Washington, DC.

Mohsenin, N.N. 1986. *Physica Propertie o Plan an Animal Materials: Structure, Physical Characteristics, and Mechanical Properties*. Gordon and Breach.

Morgan, B.C., J.E. Dexter and K.R. Preston. 2000. Relationship of kernel size of flour water absorption for Canada Western Red Spring wheat. *Cereal Chemistry* 77(3): 286–292.

Mosby, J., S.R. de Silva and G.G. Enstad. 1996. Segregation of particulate materials – Mechanisms and testers. *KONA Powder and Particle Journal* 14(May): 31–43.

Moses, J.A., V. Chelladurai, K. Alagusundaram and D.S. Jayas. 2013. Simulation of airflow distribution in stored bulk grain – a review. In *CSBE/SCGAB Annual Conference*, Saskatoon.

Muir, W.E. and R.N. Sinha. 1988. Physical properties of cereal and oilseed cultivars grown in western Canada. *Canadian Agricultural Engineering* 30(1): 51–55.

Narendran, R.B. 2018. *Segregation of canola, kidney bean, and soybean in wheat bulks during bin loading*. University of Manitoba.

Narendran, R.B., F. Jian, D.S. Jayas, P.G. Fields and N.D.G. White. 2019. Segregation of canola, kidney bean, and soybean in wheat bulks during bin loading. *Powder Technology* 344: 307–313.

Nourmohamadi-Moghadami, A., D. Zare, C.B. Singh and R.L. Stroshine. 2020a. Filling of a grain silo. Part 1: Investigation of fine material distribution in a small scale centre-filled silo. *Biosystems Engineering* 191: 145–156.

Nourmohamadi-Moghadami, A., D. Zare, R.L. Stroshine and S. Kamfiroozi. 2020b. Filling of a grain silo. Part 2: A new filling method for uniform distribution of fines in a small scale silo. *Biosystems Engineering* 191(1992): 157–167.

Noyes, R., S. Navarro and D. Armitage. 2002. *The Mechanics and Physics of Modern Grain Aeration Management*. CRC Press.

Olatunde, G., G.G. Atungulu and S. Sadaka. 2016. CFD modeling of air flow distribution in rice bin storage system with different grain mass configurations. *Biosystems Engineering* 151: 286–297.

Pagano, A.M., D.E. Crozza and S.M. Nolasco. 1998. Pressure drop through in-bulk flax seeds. *Journal of the American Oil Chemists' Society* 75(12): 1741–1747.

Pagano, A.M., D.E. Crozza and S.M. Nolasco. 2000. Airflow resistance of oat seeds: Effect of airflow direction, moisture content and foreign material. *Drying Technology* 18(1–2): 457–468.

Parker, V.R., D.S. Jayas and F. Jian. 2005. Effect of dropping height on segregation of different sized particles in stored wheat bulk. In *CSAE/SCGR Meeting*, 1–13.

Plant morphology. 2020. The Government of British Columbia.

Prasad, D.C. 1974. Abiotic and biotic characteristics of freshly-harvsted grain. University of Manitoba.

Prasad, D.C., V.E. Muir and H.A.H. Wallace. 1978. Characteristics of Freshly Harvested Wheat and Rapeseed. *Transactions of the ASAE* 21(4): 0782–0784.

Prescott, J.K. and J.W. Carson. 2000. *Analyzing and Overcoming Industrial Blending and Segregation Problems*. Springer, Dordrecht.

Samadani, A. and A. Kudrolli. 2001. Angle of repose and segregation in cohesive granular matter. *PHYSICAL REVIEW* 64: 1–9.

Santos, L.C., R. Condotta and M.C. Ferreira. 2018. Flow properties of coarse and fine sugar powders. *Journal of Food Process Engineering* 41(2): 1–10.

Schulze, D. 2008. *Powders and Bulk Solids*. Springer, Berlin, Heidelberg.

Shahbazi, F. 2011. Resistance of Bulk Chickpea Seeds to Airflow. *Journal of Agricultural Science and Technology* 13: 665–676.

Shewry, P.R. and S.J. Hey. 2015. The contribution of wheat to human diet and health. *Food and Energy Security* 4(3): 178–202.

Shimoska, A., I. Nousou, Y. Shirakawa and J. Hidaka. 2013. Effect of particle shape on size segregation of particles. *Chemical Engineering Transactions* 32: 2143–2148.

Shinohara, K. 1997. Segregation of particles. *Powder Technology* 383–393.

Shinohara, K. and B. Golman. 2002. Segregation indices of multi-sized particle mixtures during the filling of a two-dimensional hopper. *Advanced Powder Technology* 13(1): 93–107.

Shinohara, K. and S. Mlyata. 1984. Mechanism of density segregation of particles in filling vessels. *Industrial and Engineering Chemistry Process Design and Development* 23(3): 423–428.

De Silva, S.R., A. Dyroy and G.G. Enstad. 2000. *Segregation Mechanisms and Their Quantification Using Segregation Testers*. Springer.

Sinha, R.N. 1975. Effect of dockage in the infestation of wheat by some stored-product insects. *Journal of Economic Entomology* 68(5): 699–703.

Smith, E.A. and S. Sokhansanj. 1990. Moisture transport caused by natural convection in grain stores. *Journal of Agricultural Engineering Research* 47(C): 23–34.

Song, H. and J.B. Litchfield. 1991. Predicting method of terminal velocity for grains. *Transactions of the ASAE* 34(1): 225–231.

Stephens, L.E. and G.H. Foster. 1976. Grain bulk properties as affected by mechanical grain spreaders. *Transactions of the ASAE* 19(2): 354–358.

Stephens, L.E. and G.H. Foster. 1978. Bulk properties of wheat and grain sorghum as affected by a mechanical grain spreader. *Transactions of the ASAE* 21(6): 1217–1218.

Stroshine, R. 1992. *Fine Material in Grain*. 332. Wooster: North Central Regional Research.

Swaminathan, V. and D.O. Kildsig. 2002. Polydisperse powder mixtures: Effect of particle size and shape on mixture stability. *Drug Development and Industrial Pharmacy* 28(1): 41–48.

Tabatabaeefar, A. 2003. Moisture-dependent physical properties of wheat. *International Agrophysics* 17(4): 207–211.

Tahir, A.R., S. Neethirajan, D.. S. Jayas, M.A. Shahin, S.J. Symons and N.D.G. White. 2007. Evaluation of the effect of moisture content on cereal grains by digital image analysis. *Food Research International* 40: 1140–1145.

Tang, P., V.M. Puri and P.H. Patterson. 2003. Design, development, and performance of second generation primary segregation shear cell for size-segregation. In *Particulate Systems Analysis, Harrogate, U.K.*, Harrogate, U.K..

Tang, P. and V.M. Puri. 2004. Methods for minimizing segregation: A review. *Particulate Science and Technology* 22(4): 321–337.

Teferra, T.F. 2019. Engineering properties of food materials. In *Handbook of Farm, Dairy and Food Machinery Engineering*, ed. M. Kutz, Elsevier Inc..

Theimer, O.F. 1973. Cause and prevention of dust explosions in grain elevators and flour mills. *Powder Technology* 8(3–4): 137–147.

Thomson, F.M. 1997. Storage and flow of particulate solids. In *Handbook of Powder Science & Technology*, Boston: Springer.

Tilley, M., Y.R. Chen and R.A. Miller. 2012. Wheat breeding and quality evaluation in the US. In *Breadmaking: Improving Quality*, 216–236. Woodhead Publishing Limited.

Tuzun, U. and R.M. Nedderman. 1982. An investigation of the flow boundary during steady-state discharge from a funnel-flow bunker. *Powder Technology* 31(1): 27–43.

Uhl, J.B. and B.J. Lamp. 1966. Pneumatic separation of grain and straw mixtures. *Transactions of the ASAE* 244–246.

United States Department of Agriculture. 2009. Inspecting grain, practical procedures for grain handlers. Washington, DC.

United States Department of Agriculture. 2016. *Grain Grading Primer*. Washington, D. C.: United States Department of Agriculture (USDA).

Valencia-Diaz, S., A. Flores-Morales, A. Flores-Palacios and I. Perea-Arango. 2015. How does the presence of endosperm affect seed size and germination? *Botanical Sciences* 93(4): 783–789.

Venables, H.J. and J.I. Wells. 2001. Powder mixing. *Drug Development and Industrial Pharmacy* 27(7): 599–612.

Wang, K. and B.X. Fu. 2020. Inter-relationships between test weight, thousand kernel weight, kernel size distribution and their effects on durum wheat milling, semolina composition and pasta processing quality. *Foods* 9(9).

Wang, W. and J. Paliwal. 2006. Separation and identification of touching kernels and dockage components in digital images. *Canadian Biosystems Engineering* 48: 1–7.

Wasilewska, A., I. Konopka, M. Tańska and U. Wachowska. 2015. Variability of Wheat Grain Image and Content of Phenolic Compounds and Carotenoids under the Impact of Selected Novel Plant Protection Treatments. *American Journal of Experimental Agriculture* 9(2): 1–9.

Watters, F.L. 1969. The locomotor activity of Cryptolestes ferrugineus (Syephens) (Coleoptera : Cucujidae) in wheat. *Canadian Journal of Zoology* 47.

West, N.L. 1972. Aerodynamic Force Predictions. *Transactions of the ASAE* 15(3): 584–587.

Williams, J.C. and G. Shields. 1967. The segregation of granules in a vibrated bed. *Powder Technology* 1(3): 134–142.

Wu, W., L. Zhou, J. Chen, Z. Qiu and Y. He. 2018. Gain TKW: A measurement system of thousand kernel weight based on the Android platform. *Agronomy* 8(9): 1–15.

Yang, X., C.J. Bern and C.R. Hurburgh. 1990. Airflow resistance of cleanings removed from corn. *Transactions of the ASAE* 33(4): 1299–1302.

Zaalouk, A.K. and F.I. Zabady. 2009. Effect of moisture content on angle of repose and friction coefficient of wheat grain. *Misr Journal of Agricultural Engineering* 26(1): 418–427.

Zewdu, A.D. 2007. Aerodynamic properties of tef grain and straw material. *Biosystems Engineering* 98(3): 304–309.

Zhou, B., K.E. Ileleji and G. Ejeta. 2008. Physical property relationships of bulk corn stover particles. *Transactions of the ASABE* 51(2): 581–590.

APPENDIX A

Weight of different groups of impurities removed from collected samples.[1]

Layer	Radius	Location	Position	Sample weight (kg)	Stones (g)	Other grains (g)	Other particles (g)	Shrunken and broken kernels (SBK) (g)	Fine particle (g)	Dust and Fragments (g)
1	1	1	1	10.32	2.755	1.891	8.568	16.202	36.173	9.923
1	1	1	2	9.25	0.000	2.863	7.486	14.319	31.766	11.893
1	1	2	1	9.77	0.000	2.243	3.379	17.730	18.623	3.591
1	1	2	2	11.36	0.000	1.406	4.800	13.891	17.887	4.058
1	1	3	1	10.04	0.000	1.270	1.959	9.276	9.193	1.177
1	1	3	2	9.78	0.000	0.640	3.448	11.709	13.322	2.055
1	1	4	1	12.30	0.000	1.657	12.680	13.819	13.824	1.657
1	1	4	2	11.32	0.000	1.033	11.723	12.588	12.500	1.146
1	1	5	1	10.17	0.000	0.878	13.484	18.883	8.531	1.222
1	1	5	2	11.21	0.000	1.124	15.067	17.234	11.367	1.502
1	2	2	1	10.86	0.000	2.208	4.447	15.701	16.144	4.006
1	2	2	2	11.09	0.000	1.659	3.681	13.966	19.716	5.145
1	2	3	1	11.33	0.000	1.127	2.211	11.869	14.988	2.664
1	2	3	2	9.88	0.000	2.319	1.633	12.002	16.741	1.936
1	2	4	1	10.50	0.000	1.250	9.785	12.677	14.006	0.983
1	2	4	2	11.89	0.000	0.586	10.086	10.864	14.553	1.834
1	2	5	1	10.76	0.000	0.972	16.213	16.946	12.511	1.347
1	2	5	2	12.44	0.000	1.006	17.400	17.555	10.180	2.103
1	3	2	1	11.88	0.000	1.563	2.806	14.311	21.227	5.168
1	3	2	2	10.51	0.000	2.438	4.249	14.852	18.875	2.975
1	3	3	1	10.93	0.000	1.257	3.420	12.355	15.466	1.702
1	3	3	2	11.42	0.000	1.299	2.283	13.337	16.848	3.118
1	3	4	1	12.78	0.000	1.988	12.554	9.696	12.058	2.046
1	3	4	2	10.22	0.000	1.302	14.708	11.450	13.192	1.249
1	3	5	1	10.05	0.000	1.737	15.310	20.892	13.414	2.373
1	3	5	2	11.40	0.000	0.855	16.215	18.005	11.377	1.401
2	1	1	1	10.56	0.830	5.149	15.647	18.079	42.481	11.318
2	1	1	2	11.67	1.041	4.323	13.464	16.895	37.249	15.073
2	1	2	1	9.59	0.000	3.655	9.055	14.988	26.146	3.292
2	1	2	2	10.00	0.000	4.326	10.207	15.227	28.540	5.200
2	1	3	1	11.31	0.000	2.479	5.854	17.549	15.114	2.076
2	1	3	2	10.85	0.000	3.110	4.869	14.815	11.058	1.816
2	1	4	1	10.39	0.000	3.492	8.419	11.951	6.766	1.364
2	1	4	2	9.77	0.000	2.261	11.872	13.055	9.664	0.770
2	1	5	1	11.28	0.000	3.085	26.290	27.961	14.566	1.155
2	1	5	2	12.80	0.000	2.315	21.505	23.645	10.463	1.403
2	2	2	1	11.91	0.000	3.808	11.378	17.238	21.529	6.343
2	2	2	2	12.12	0.000	5.215	12.855	15.455	25.770	5.830
2	2	3	1	11.37	0.000	4.426	8.400	15.830	18.603	2.333
2	2	3	2	11.44	0.000	3.711	5.507	14.202	14.008	2.678
2	2	4	1	10.60	0.000	3.087	10.849	12.399	11.315	1.505
2	2	4	2	10.65	0.000	3.175	9.344	11.507	10.065	1.364
2	2	5	1	11.11	0.000	2.899	17.490	19.000	9.844	2.121
2	2	5	2	10.76	0.000	3.051	19.621	21.861	10.576	1.476
2	3	2	1	13.41	0.000	4.845	10.877	18.550	30.430	5.567
2	3	2	2	12.53	0.000	4.341	8.349	15.071	26.649	4.604

[1] Layers are numbered from bottom being 1, location increases from center to wall, and position refers 1 as top and 2 as bottom. Radius implies replicates because heap formation was symmetrical.

2	3	3	1	12.34	0.000	4.204	3.211	14.422	16.066	4.485
2	3	3	2	10.94	0.000	3.555	5.434	11.946	17.249	1.996
2	3	4	1	11.19	0.000	2.822	12.610	13.221	12.468	1.290
2	3	4	2	13.00	0.000	2.503	13.853	15.647	10.011	2.063
2	3	5	1	11.33	0.000	1.860	20.415	17.933	11.455	0.993
2	3	5	2	12.74	0.000	2.211	22.590	24.412	12.423	1.885
3	1	1	1	12.76	1.847	26.680	8.432	26.983	92.510	61.134
3	1	1	2	11.70	0.620	24.137	9.509	21.930	75.196	65.245
3	1	2	1	10.94	0.000	16.058	4.803	15.618	21.455	9.523
3	1	2	2	10.05	0.000	18.133	3.500	18.872	18.296	8.017
3	1	3	1	11.40	0.000	6.705	4.745	17.634	13.029	3.066
3	1	3	2	11.84	0.000	5.411	2.789	16.008	11.447	4.212
3	1	4	1	11.01	0.000	4.450	11.234	20.707	12.823	2.991
3	1	4	2	11.25	0.000	2.713	10.385	22.149	11.271	2.545
3	1	5	1	10.78	0.000	2.551	17.007	27.855	9.620	2.619
3	1	5	2	10.55	0.000	4.769	14.693	30.361	11.492	3.050
3	2	2	1	11.35	0.000	20.360	4.949	20.503	16.562	8.714
3	2	2	2	12.20	0.000	21.791	6.373	18.689	19.275	8.862
3	2	3	1	12.52	0.000	7.108	2.461	17.033	12.592	2.944
3	2	3	2	11.37	0.000	11.302	3.617	17.256	15.063	3.009
3	2	4	1	13.77	0.000	2.400	9.548	23.723	17.692	2.856
3	2	4	2	10.82	0.000	2.215	8.119	19.415	14.820	2.149
3	2	5	1	11.43	0.000	2.410	13.772	34.633	13.812	2.704
3	2	5	2	10.13	0.000	3.019	15.592	29.677	14.218	2.062
3	3	2	1	10.42	0.000	17.802	5.283	19.647	23.519	8.600
3	3	2	2	11.78	0.000	14.555	6.444	20.888	19.444	11.367
3	3	3	1	9.62	0.000	10.356	3.792	17.429	14.508	2.566
3	3	3	2	10.88	0.000	7.688	1.985	19.063	15.810	3.937
3	3	4	1	12.43	0.000	2.159	10.672	22.340	11.555	2.415
3	3	4	2	10.47	0.000	2.411	12.900	24.171	13.173	1.801
3	3	5	1	12.48	0.000	3.318	14.942	31.218	8.644	1.945
3	3	5	2	13.22	0.000	1.484	16.205	25.805	12.028	2.589
4	1	1	1	13.72	0.000	3.000	29.152	27.053	49.700	19.344
4	1	1	2	11.86	0.000	2.415	23.326	21.850	37.264	32.600
4	1	2	1	13.40	0.000	1.308	9.080	18.553	19.123	8.286
4	1	2	2	11.32	0.000	1.470	7.215	19.820	23.440	7.201
4	1	3	1	12.89	0.000	0.500	7.772	21.633	15.127	2.455
4	1	3	2	11.51	0.000	1.062	6.349	19.032	16.007	2.682
4	1	4	1	9.85	0.000	0.823	13.985	17.234	13.952	0.850
4	1	4	2	11.37	0.000	0.677	13.597	18.914	13.806	1.737
4	1	5	1	10.95	0.000	1.450	19.872	20.953	12.262	1.904
4	1	5	2	12.22	0.000	0.542	16.672	24.168	10.275	1.422
4	2	2	1	11.74	0.000	1.705	5.316	16.624	26.570	7.618
4	2	2	2	12.71	0.000	1.303	3.095	19.711	22.062	9.055
4	2	3	1	10.42	0.000	1.256	4.211	14.328	15.915	2.110
4	2	3	2	11.05	0.000	0.861	2.251	17.650	17.764	3.217
4	2	4	1	11.90	0.000	1.112	10.844	20.471	12.799	2.093
4	2	4	2	9.76	0.000	1.094	11.127	22.700	12.651	1.073
4	2	5	1	10.61	0.000	0.750	18.300	28.102	11.005	1.324
4	2	5	2	11.92	0.000	1.221	20.618	29.323	13.418	1.689
4	3	2	1	11.24	0.000	2.127	7.212	21.312	20.101	7.300
4	3	2	2	11.48	0.000	1.366	5.380	18.447	17.532	9.628
4	3	3	1	11.66	0.000	0.845	4.962	15.750	18.090	2.574
4	3	3	2	12.20	0.000	1.419	5.124	16.009	17.348	2.801
4	3	4	1	11.61	0.000	0.997	12.318	20.911	12.500	1.255
4	3	4	2	11.19	0.000	1.105	9.455	18.455	13.972	1.492
4	3	5	1	12.27	0.000	0.867	16.736	28.284	13.037	2.370
4	3	5	2	10.75	0.000	0.000	19.665	24.376	9.249	1.606
5	1	1	1	11.92	0.000	3.740	22.272	30.303	103.726	83.145
5	1	1	2	11.34	0.000	4.243	25.463	26.516	128.501	71.619

5	1	2	1	12.48	0.000	2.902	12.982	21.822	35.825	11.607
5	1	2	2	10.96	0.000	2.220	14.117	24.555	28.005	8.734
5	1	3	1	10.73	0.000	1.538	11.276	21.793	19.277	5.812
5	1	3	2	12.17	0.000	2.303	10.013	22.500	26.018	7.043
5	1	4	1	11.22	0.000	1.206	19.723	25.521	19.123	3.125
5	1	4	2	11.53	0.000	0.963	18.600	28.314	16.412	2.678
5	1	5	1	10.74	0.000	1.022	27.812	38.600	22.808	3.049
5	1	5	2	10.61	0.000	0.864	31.542	41.827	27.393	3.320
5	2	2	1	11.90	0.000	3.110	12.763	20.418	26.844	10.008
5	2	2	2	10.54	0.000	2.308	12.855	22.277	30.619	11.492
5	2	3	1	10.95	0.000	2.405	9.110	18.472	21.756	5.652
5	2	3	2	12.47	0.000	1.862	8.492	23.656	25.029	7.877
5	2	4	1	9.86	0.000	0.866	19.106	19.948	18.919	3.238
5	2	4	2	11.14	0.000	1.249	17.882	24.638	17.236	4.100
5	2	5	1	11.96	0.000	0.503	31.240	35.918	31.735	4.218
5	2	5	2	9.97	0.000	1.045	33.788	32.755	22.154	2.812
5	3	2	1	13.40	0.000	2.540	13.689	26.753	31.310	8.209
5	3	2	2	11.60	0.000	2.744	11.480	23.400	33.457	9.364
5	3	3	1	10.35	0.000	2.710	12.272	21.233	19.558	5.084
5	3	3	2	11.73	0.000	2.105	9.215	19.840	23.932	6.468
5	3	4	1	12.68	0.000	3.330	18.303	23.753	20.210	2.914
5	3	4	2	10.84	0.000	2.208	21.785	27.688	17.792	3.515
5	3	5	1	12.10	0.000	2.160	38.550	44.453	32.503	4.354
5	3	5	2	10.57	0.000	1.144	31.072	37.551	28.236	3.180

APPENDIX B

The weight and test weight of small and large wheat kernels in clean wheat.[2]

Layer	Radius	Location	Position	Sample weight (kg)	Small kernels		Large kernels	
					Weight (kg)	Test Weight (g/0.5L)	Weight (kg)	Test Weight (g/0.5L)
1	1	1	1	10.32	2.88	412.3	7.44	418.8
1	1	1	2	9.25	2.10	411.5	7.15	419.2
1	1	2	1	9.77	2.51	412.9	7.26	417.7
1	1	2	2	11.36	3.17	411.3	8.19	419.0
1	1	3	1	10.04	2.29	412.7	7.75	418.1
1	1	3	2	9.78	2.48	410.8	7.30	417.3
1	1	4	1	12.30	2.88	410.6	9.42	418.2
1	1	4	2	11.32	3.11	412.6	8.21	421.5
1	1	5	1	10.17	2.52	411.2	7.65	417.1
1	1	5	2	11.21	2.86	411.0	8.35	419.7
1	2	2	1	10.86	2.91	414.1	7.95	416.2
1	2	2	2	11.09	2.65	411.3	8.44	417.7
1	2	3	1	11.33	2.30	411.6	9.03	419.0
1	2	3	2	9.88	2.44	412.6	7.44	418.3
1	2	4	1	10.50	2.91	410.7	7.59	419.5
1	2	4	2	11.89	3.11	411.3	8.78	418.4
1	2	5	1	10.76	2.77	413.7	7.99	419.9
1	2	5	2	12.44	2.75	411.6	9.69	417.0
1	3	2	1	11.88	2.96	411.5	8.92	418.6
1	3	2	2	10.51	2.84	410.5	7.67	416.3
1	3	3	1	10.93	2.61	409.8	8.32	419.9
1	3	3	2	11.42	2.92	412.4	8.50	417.5
1	3	4	1	12.78	2.63	411.2	10.15	418.2
1	3	4	2	10.22	2.52	411.7	7.70	420.4
1	3	5	1	10.05	2.40	410.8	7.65	418.6
1	3	5	2	11.40	2.66	411.6	8.74	419.6
2	1	1	1	10.56	3.14	411.9	7.42	419.2
2	1	1	2	11.67	2.84	411.5	8.83	419.5
2	1	2	1	9.59	2.55	411.2	7.04	420.2
2	1	2	2	10.00	2.71	411.1	7.29	417.6
2	1	3	1	11.31	2.75	410.8	8.56	421.1
2	1	3	2	10.85	2.44	410.2	8.41	419.0
2	1	4	1	10.39	2.35	415.8	8.04	420.0
2	1	4	2	9.77	2.41	411.8	7.36	418.0
2	1	5	1	11.28	3.04	412.8	8.24	417.6
2	1	5	2	12.80	2.86	410.3	9.94	418.5
2	2	2	1	11.91	3.12	412.1	8.79	417.2
2	2	2	2	12.12	2.98	411.5	9.14	417.0
2	2	3	1	11.37	2.85	411.0	8.52	418.8
2	2	3	2	11.44	2.24	411.0	9.20	419.7
2	2	4	1	10.60	2.51	412.7	8.09	420.3
2	2	4	2	10.65	2.88	415.3	7.77	419.6
2	2	5	1	11.11	2.37	408.3	8.74	418.5
2	2	5	2	10.76	2.56	411.9	8.20	418.0
2	3	2	1	13.41	3.55	412.4	9.86	418.7
2	3	2	2	12.53	2.81	412.1	9.72	419.9

[2] Layers are numbered from bottom being 1, location increases from center to wall, and position refers 1 as top and 2 as bottom. Radius implies replicates because heap formation was symmetrical.

2	3	3	1	12.34	2.97	412.5	9.37	417.5
2	3	3	2	10.94	2.83	414.7	8.11	419.0
2	3	4	1	11.19	3.11	415.0	8.08	419.5
2	3	4	2	13.00	2.96	411.2	10.04	418.4
2	3	5	1	11.33	2.65	411.8	8.68	417.0
2	3	5	2	12.74	3.20	412.2	9.54	418.2
3	1	1	1	12.76	3.92	409.9	8.84	419.0
3	1	1	2	11.70	2.74	412.3	8.96	415.6
3	1	2	1	10.94	3.00	411.7	7.94	417.5
3	1	2	2	10.05	2.86	413.5	7.19	419.1
3	1	3	1	11.40	2.85	412.0	8.55	419.2
3	1	3	2	11.84	2.81	413.9	9.03	419.5
3	1	4	1	11.01	2.44	411.6	8.57	418.7
3	1	4	2	11.25	2.75	413.5	8.50	418.7
3	1	5	1	10.78	2.89	411.9	7.89	418.5
3	1	5	2	10.55	2.17	411.2	8.38	418.0
3	2	2	1	11.35	2.99	412.3	8.36	418.4
3	2	2	2	12.20	2.87	411.7	9.33	419.2
3	2	3	1	12.52	3.04	411.5	9.48	417.6
3	2	3	2	11.37	2.55	413.6	8.82	420.0
3	2	4	1	13.77	3.92	412.6	9.85	417.7
3	2	4	2	10.82	2.21	411.7	8.61	418.2
3	2	5	1	11.43	2.65	410.0	8.78	417.3
3	2	5	2	10.13	2.43	411.9	7.70	418.6
3	3	2	1	10.42	2.81	411.6	7.61	415.2
3	3	2	2	11.78	3.10	410.3	8.68	418.1
3	3	3	1	9.62	2.02	412.7	7.60	418.5
3	3	3	2	10.88	2.85	411.0	8.03	419.6
3	3	4	1	12.43	3.42	408.7	9.01	417.7
3	3	4	2	10.47	2.32	411.6	8.15	418.3
3	3	5	1	12.48	3.04	410.6	9.44	419.8
3	3	5	2	13.22	2.67	412.9	10.55	416.7
4	1	1	1	13.72	3.12	412.1	10.60	416.9
4	1	1	2	11.86	2.99	411.8	8.87	417.5
4	1	2	1	13.40	3.42	412.4	9.98	418.7
4	1	2	2	11.32	3.25	416.3	8.07	419.3
4	1	3	1	12.89	3.02	412.5	9.87	419.0
4	1	3	2	11.51	2.24	412.9	9.27	422.1
4	1	4	1	9.85	2.54	412.3	7.31	418.8
4	1	4	2	11.37	2.41	412.8	8.96	417.2
4	1	5	1	10.95	2.80	414.0	8.15	418.3
4	1	5	2	12.22	2.97	413.2	9.25	418.2
4	2	2	1	11.74	2.73	412.6	9.01	418.1
4	2	2	2	12.71	3.42	413.1	9.29	418.5
4	2	3	1	10.42	2.65	410.9	7.77	422.3
4	2	3	2	11.05	2.32	412.0	8.73	419.6
4	2	4	1	11.90	2.81	412.0	9.09	418.4
4	2	4	2	9.76	2.86	413.5	6.90	417.4
4	2	5	1	10.61	2.04	411.3	8.57	418.2
4	2	5	2	11.92	2.75	412.1	9.17	418.0
4	3	2	1	11.24	2.68	411.5	8.56	417.6
4	3	2	2	11.48	2.97	412.2	8.51	418.1
4	3	3	1	11.66	3.14	409.6	8.52	421.5
4	3	3	2	12.20	3.22	413.2	8.98	419.7
4	3	4	1	11.61	2.68	411.8	8.93	418.7
4	3	4	2	11.19	2.75	412.1	8.44	418.6
4	3	5	1	12.27	3.13	411.6	9.14	418.2
4	3	5	2	10.75	2.50	412.0	8.25	418.5
5	1	1	1	11.92	2.94	409.0	8.98	416.6
5	1	1	2	11.34	2.80	411.1	8.54	418.3

5	1	2	1	12.48	2.66	411.3	9.82	417.5
5	1	2	2	10.96	2.91	412.1	8.05	415.5
5	1	3	1	10.73	2.77	410.0	7.96	419.0
5	1	3	2	12.17	3.01	414.9	9.16	418.3
5	1	4	1	11.22	2.72	411.0	8.50	418.0
5	1	4	2	11.53	2.65	411.8	8.88	419.4
5	1	5	1	10.74	2.71	411.2	8.03	418.7
5	1	5	2	10.61	2.33	408.7	8.28	419.1
5	2	2	1	11.90	2.82	414.2	9.08	417.9
5	2	2	2	10.54	3.05	411.3	7.49	417.6
5	2	3	1	10.95	2.56	413.3	8.39	418.3
5	2	3	2	12.47	3.03	412.4	9.44	418.0
5	2	4	1	9.86	2.71	412.7	7.15	418.8
5	2	4	2	11.14	2.68	410.6	8.46	417.2
5	2	5	1	11.96	2.57	409.3	9.39	418.1
5	2	5	2	9.97	2.59	413.7	7.38	417.5
5	3	2	1	13.40	3.24	413.2	10.16	418.2
5	3	2	2	11.60	2.99	411.9	8.61	416.3
5	3	3	1	10.35	2.50	412.0	7.85	417.3
5	3	3	2	11.73	2.92	412.8	8.81	417.7
5	3	4	1	12.68	3.25	414.1	9.43	418.1
5	3	4	2	10.84	2.98	412.5	7.86	419.2
5	3	5	1	12.10	3.16	411.5	8.94	416.8
5	3	5	2	10.57	2.40	412.8	8.17	418.3

APPENDIX C

Test weight and true density of clean and unclean wheat, thousand kernel weight (TKW) and dimensions of wheat kernels (L=Length, W=Width and T= Thickness).[3]

Layer	Radius	Location	Position	Test Weight (g/0.5L)		True Density (kg/m3)		TKW (g)	Kernels Dimensions (mm)		
				Clean Wheat	Unclean Wheat	Clean Wheat	Unclean Wheat		L	W	T
1	1	1	1	417.5	412.4	1433.6	1428.3	35.836	6.06	2.97	2.76
1	1	1	2	415.6	413.8	1442.8	1429.3	35.182	6.73	3.04	2.93
1	1	2	1	414.5	414.0	1434.3	1429.1	33.599	6.27	3.05	2.86
1	1	2	2	417.0	415.4	1436.3	1426.2	35.298	5.29	2.60	2.40
1	1	3	1	416.9	414.4	1443.0	1432.0	35.488	6.04	2.89	2.55
1	1	3	2	416.6	416.1	1436.8	1427.5	34.324	6.52	3.19	2.86
1	1	4	1	417.9	416.4	1445.2	1429.0	35.031	6.38	3.07	2.78
1	1	4	2	418.7	417.0	1438.5	1428.5	35.119	5.98	3.03	2.77
1	1	5	1	415.9	413.4	1439.1	1430.2	35.110	6.20	2.72	2.69
1	1	5	2	417.2	414.0	1434.4	1425.7	34.830	5.91	3.15	2.76
1	2	2	1	415.1	413.4	1438.1	1434.7	33.623	5.13	2.97	2.73
1	2	2	2	415.8	412.8	1433.0	1431.8	34.960	6.36	3.05	2.86
1	2	3	1	417.2	415.0	1439.1	1428.5	34.213	5.74	2.80	2.57
1	2	3	2	416.7	415.9	1439.9	1432.2	35.837	5.99	2.93	2.95
1	2	4	1	418.1	415.9	1440.2	1429.1	34.776	6.50	3.08	2.83
1	2	4	2	418.3	415.0	1437.5	1429.8	34.845	7.03	3.16	2.69
1	2	5	1	416.1	412.5	1432.3	1427.1	35.196	6.43	2.95	2.76
1	2	5	2	415.8	413.1	1433.8	1425.0	34.900	5.75	3.12	2.98
1	3	2	1	415.4	414.6	1441.2	1431.0	35.424	6.24	2.83	2.67
1	3	2	2	416.0	414.4	1440.1	1433.3	35.093	4.97	3.21	2.78
1	3	3	1	416.0	415.4	1440.7	1431.1	35.306	6.20	3.08	2.74
1	3	3	2	417.9	414.8	1441.5	1427.5	36.291	6.76	3.34	2.46
1	3	4	1	416.2	416.0	1438.2	1429.8	34.601	5.78	3.07	2.71
1	3	4	2	416.8	415.1	1440.3	1431.1	34.683	6.49	2.93	3.12
1	3	5	1	417.0	412.6	1448.2	1427.9	35.209	6.66	3.07	2.75
1	3	5	2	415.1	411.6	1441.9	1428.9	35.100	6.20	3.00	2.67
2	1	1	1	416.8	413.1	1444.1	1427.2	35.224	6.02	3.00	2.81
2	1	1	2	415.6	413.9	1440.9	1432.0	34.721	6.13	3.15	2.77
2	1	2	1	419.0	417.0	1442.0	1433.7	35.283	5.28	3.42	2.87
2	1	2	2	415.1	412.5	1438.5	1432.6	34.377	5.92	3.02	2.76
2	1	3	1	419.3	418.5	1439.2	1431.9	35.033	6.44	2.79	2.55
2	1	3	2	416.9	417.1	1436.6	1425.5	34.955	6.27	3.03	2.94
2	1	4	1	421.4	419.0	1446.2	1433.1	34.161	5.93	2.93	2.71
2	1	4	2	418.3	418.0	1442.5	1430.0	33.780	6.04	2.95	2.65
2	1	5	1	416.2	413.6	1442.7	1429.7	35.600	6.24	3.35	2.82
2	1	5	2	415.9	412.6	1443.9	1428.6	35.268	6.90	3.13	2.89
2	2	2	1	414.0	412.4	1435.6	1434.0	34.801	5.52	3.03	2.78
2	2	2	2	415.8	412.7	1442.1	1431.8	35.749	6.33	2.98	2.90
2	2	3	1	417.0	416.2	1440.7	1429.8	35.172	5.98	2.98	2.65
2	2	3	2	417.5	416.1	1432.9	1424.2	34.619	5.81	3.14	2.82
2	2	4	1	419.1	418.7	1442.0	1427.5	34.196	6.12	3.03	2.94
2	2	4	2	419.5	416.4	1439.2	1431.8	34.578	5.53	3.19	2.75
2	2	5	1	417.6	413.5	1440.4	1428.5	34.526	6.25	2.90	2.72
2	2	5	2	415.8	411.4	1439.9	1430.7	34.749	6.03	3.10	2.82
2	3	2	1	415.8	415.2	1443.1	1431.7	34.725	5.94	2.95	2.87

[3] Layers are numbered from bottom being 1, location increases from center to wall, and position refers 1 as top and 2 as bottom. Radius implies replicates because heap formation was symmetrical.

2	3	2	2	416.3	411.5	1436.7	1429.1	34.930	5.36	3.11	2.93
2	3	3	1	417.1	413.6	1438.5	1432.8	36.408	6.60	3.20	3.11
2	3	3	2	416.6	415.1	1438.2	1430.8	35.126	6.46	2.94	2.73
2	3	4	1	415.7	414.5	1437.3	1429.2	34.697	5.54	3.12	2.81
2	3	4	2	417.7	417.5	1442.1	1429.8	35.006	6.43	3.02	2.77
2	3	5	1	415.6	412.7	1440.5	1426.2	34.771	5.16	2.85	2.50
2	3	5	2	416.7	412.5	1437.7	1429.8	33.205	6.04	3.01	3.06
3	1	1	1	415.6	412.3	1431.6	1430.7	34.139	5.65	2.95	2.80
3	1	1	2	414.9	412.4	1438.7	1429.9	33.766	6.18	3.19	2.80
3	1	2	1	415.8	414.6	1439.1	1425.1	35.488	6.31	3.08	2.72
3	1	2	2	416.5	416.4	1436.5	1433.8	34.774	6.85	2.99	2.63
3	1	3	1	418.0	417.5	1444.8	1431.7	34.845	6.17	2.88	2.74
3	1	3	2	418.2	416.9	1437.1	1429.0	34.304	6.41	2.96	2.88
3	1	4	1	417.3	415.6	1435.5	1430.1	33.843	5.88	2.81	2.72
3	1	4	2	416.7	416.5	1438.2	1427.9	34.853	5.78	3.13	2.75
3	1	5	1	414.6	409.1	1436.2	1428.8	34.631	5.69	2.65	2.67
3	1	5	2	417.2	413.7	1440.5	1430.5	34.987	6.35	2.92	2.74
3	2	2	1	416.8	413.6	1436.5	1429.8	34.863	6.19	3.26	2.75
3	2	2	2	416.3	414.8	1438.1	1432.2	36.144	6.49	2.89	2.64
3	2	3	1	418.0	416.6	1442.2	1431.7	34.790	6.31	2.91	2.91
3	2	3	2	417.6	417.6	1439.9	1429.6	33.709	6.12	3.12	2.82
3	2	4	1	416.5	415.1	1429.8	1428.1	34.943	6.06	3.03	2.61
3	2	4	2	415.2	415.1	1435.2	1431.9	35.291	6.44	3.07	2.88
3	2	5	1	416.0	410.2	1438.8	1434.5	35.336	6.18	3.20	2.76
3	2	5	2	415.5	411.9	1435.9	1428.8	35.276	5.99	2.97	2.90
3	3	2	1	416.0	415.0	1432.1	1433.0	34.795	5.70	2.93	2.72
3	3	2	2	417.2	416.7	1440.3	1430.4	35.099	5.87	3.17	3.00
3	3	3	1	418.1	417.5	1439.8	1426.1	35.031	6.00	2.91	2.85
3	3	3	2	418.0	417.1	1441.8	1421.5	34.317	6.11	2.87	2.70
3	3	4	1	416.2	415.3	1444.6	1431.9	34.643	5.89	3.13	2.82
3	3	4	2	417.0	415.9	1441.2	1429.5	34.951	6.37	3.02	2.89
3	3	5	1	416.5	412.4	1440.7	1431.7	35.369	6.25	3.11	2.83
3	3	5	2	415.8	414.7	1437.5	1428.8	34.780	5.65	3.00	2.78
4	1	1	1	415.5	413.2	1438.5	1426.2	36.074	6.00	3.31	2.96
4	1	1	2	417.4	414.5	1440.3	1430.5	35.726	6.64	3.05	2.75
4	1	2	1	418.3	417.6	1439.5	1429.1	35.061	6.42	2.84	2.54
4	1	2	2	418.2	416.5	1440.8	1428.9	34.480	6.16	2.97	2.80
4	1	3	1	418.9	417.1	1436.5	1433.2	35.350	5.68	2.88	2.84
4	1	3	2	417.7	416.1	1441.2	1431.5	35.550	6.03	3.16	2.87
4	1	4	1	417.2	417.0	1441.0	1425.0	35.297	5.83	2.98	2.76
4	1	4	2	416.4	414.9	1434.5	1430.5	33.402	5.49	3.10	2.88
4	1	5	1	417.0	412.4	1433.7	1431.8	35.674	6.12	2.65	2.68
4	1	5	2	418.0	415.7	1441.0	1436.8	34.703	6.47	3.05	2.89
4	2	2	1	418.6	416.0	1438.7	1429.9	35.115	6.23	3.08	2.79
4	2	2	2	417.1	415.6	1440.5	1428.6	34.647	6.35	3.41	2.59
4	2	3	1	418.1	416.6	1438.2	1432.2	35.292	6.66	2.96	2.82
4	2	3	2	417.7	416.8	1439.9	1430.7	35.991	6.82	2.70	2.55
4	2	4	1	416.9	415.8	1430.2	1427.5	34.952	5.83	3.24	3.01
4	2	4	2	416.2	416.5	1437.7	1427.7	34.008	6.53	3.21	2.93
4	2	5	1	417.5	415.1	1438.5	1430.8	35.570	6.30	3.08	2.83
4	2	5	2	417.1	414.8	1439.5	1429.6	34.315	5.65	3.02	2.80
4	3	2	1	416.0	414.0	1441.3	1431.6	35.039	5.71	2.97	2.65
4	3	2	2	416.8	416.0	1446.3	1432.1	34.896	6.17	3.10	2.87
4	3	3	1	418.8	415.3	1452.1	1429.5	36.118	5.87	2.86	2.37
4	3	3	2	417.5	416.5	1438.9	1431.8	35.206	6.34	2.79	2.71
4	3	4	1	416.8	416.5	1441.5	1431.7	35.308	6.06	2.95	2.64
4	3	4	2	415.6	415.1	1437.1	1432.5	34.293	5.80	3.03	2.74
4	3	5	1	417.2	415.9	1437.2	1429.5	35.088	6.29	2.90	2.78
4	3	5	2	417.8	414.6	1435.8	1430.8	35.380	6.51	3.08	2.89
5	1	1	1	417.1	412.9	1438.7	1435.6	34.991	6.36	2.64	2.59

5	1	1	2	417.7	411.7	1442.9	1433.5	34.535	5.69	2.97	2.82
5	1	2	1	415.3	412.3	1439.0	1432.9	35.205	6.10	2.80	2.52
5	1	2	2	415.4	411.5	1440.3	1430.5	36.220	6.29	2.67	2.65
5	1	3	1	416.9	413.7	1447.1	1433.6	35.268	6.08	2.76	2.67
5	1	3	2	416.5	414.6	1441.1	1428.5	34.041	6.14	3.18	2.92
5	1	4	1	418.1	415.4	1437.2	1430.0	34.516	6.22	2.97	2.80
5	1	4	2	416.2	415.5	1439.2	1431.6	35.179	6.78	2.89	2.35
5	1	5	1	417.8	408.8	1443.6	1430.2	35.075	5.33	2.92	2.66
5	1	5	2	416.9	412.7	1441.3	1426.5	34.856	6.55	2.86	2.62
5	2	2	1	416.8	414.7	1447.1	1434.7	35.353	6.01	2.91	2.77
5	2	2	2	415.4	411.7	1439.2	1435.5	35.234	5.54	3.14	3.10
5	2	3	1	417.2	414.3	1435.0	1433.1	35.262	6.59	3.01	2.72
5	2	3	2	416.7	415.9	1438.0	1430.9	35.763	6.33	2.74	2.61
5	2	4	1	418.0	415.0	1441.2	1429.9	35.989	6.12	3.05	2.90
5	2	4	2	416.6	416.1	1441.9	1434.4	35.176	5.37	2.74	2.56
5	2	5	1	417.1	411.1	1443.2	1424.6	34.608	6.01	2.95	2.93
5	2	5	2	418.2	413.3	1440.4	1423.4	33.958	6.23	3.12	2.81
5	3	2	1	415.3	413.2	1442.6	1434.7	34.513	6.68	2.76	2.70
5	3	2	2	415.9	412.5	1435.1	1430.3	35.383	6.01	3.02	2.75
5	3	3	1	415.1	413.5	1439.2	1432.2	35.807	6.12	3.28	2.41
5	3	3	2	417.2	412.7	1441.3	1431.8	35.022	5.83	3.22	2.98
5	3	4	1	417.5	415.4	1442.5	1432.0	33.943	6.04	2.99	2.82
5	3	4	2	417.1	414.7	1435.7	1429.9	34.328	5.30	3.00	2.69
5	3	5	1	418.5	410.3	1442.9	1422.3	34.696	6.28	3.11	2.86
5	3	5	2	417.9	411.5	1444.9	1427.1	34.900	5.75	3.09	2.80