Grain dust characterization and repeated handling in pilot-scale bucket elevator legs

by

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Abstract

Moving and transferring grains in large quantities generate grain dust that poses both health and safety hazards. For the first study, two pilot-scale bucket elevator legs with front-feed and back-feed directions were used to examine the effect of repeated handling on soybean dust quantity, particle size, particle size distribution (PSD), and shape characteristics (high sensitivity (HS) circularity, aspect ratio (AR), and elongation). The effect of soybean grades [U.S. No. 1 and U.S. No. 3] and elevator types on various parameters was also studied. The dust samples were collected at different sampling points of the bucket elevator using glass fiber filters. Particle size and shape analysis were determined using the Malvern Morphologi G3 SE. Results showed significant differences ($p<0.05$) in the mass of dust collected (m_d) among soybean grades and elevator types in the first run. A general decreasing trend in m_d was observed for all elevator types and soybean grades with sampling points 1 and 2 having the highest m_d. The circle equivalent diameter of the dust particles ranged from 3.00 µm to 8.36 µm. Meanwhile, the overall PSD across grades, runs, and sampling points did not significantly vary ($p>0.05$).

For the second study, dust samples from wheat, corn, soybean, rice, and milo were obtained and tested in five replicates for particle size, PSD, and shape characteristics (circularity, HS circularity, convexity, elongation, solidity, and AR) using Morphologi G3 SE. Flowability and floodability indices were determined using Carr indices chart based on aerated and packed bulk density (ρ_p) measurements; angles of repose, spatula, fall, and difference; compressibility; cohesion; and dispersibility in the Hosokawa Powder Tester PT-R. Results showed significant differences in ρ_p, cohesion, elongation, and AR among the five grain dust types. Soybean dust exhibited the highest flowability (34.70) and floodability (64.25) indices while milo dust exhibited the lowest (flowability index, 11.60; floodability index, 9.70). Very strong positive correlation was

observed for floodability index and dispersibility while very strong negative correlation was observed for cohesion and flowability index. Determining the flowability, floodability, and particle size and shape characteristics of various grain dust types is critical in the design of bulk handling equipment that may reduce the hazard associated with explosion and unexpected spills. Quantitative values of dust properties are also important as these provide the necessary data to construct modeling and simulation experiments of dust handling, emission, and explosion.

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Chapter 1 - Introduction

1.1 Problem Statement

The United States (US) is the world's largest producer and exporter of grains. In 2020, it produced 373 million bushels of sorghum, 228 million hundredweights (cwt) of rice, 4.14 billion bushels of soybeans, 14.2 billion bushels of corn, and 1.8 billion bushels of winter, durum, and other spring wheat (Grainnet, 2021; Sowell & Swearingen, 2021). Alongside massive grain production is the production of large volumes of grain dust which are emitted every time grains are handled. The most common facility dedicated to receiving, storing, and distributing grains in bulk is grain elevators. They are also one of the most susceptible areas for dust explosions. In fact, in the past ten years (2011-2020), 46 out of 81 recorded dust explosions happened in grain elevators (Ambrose, 2020).

Grain dust are particulate matter containing approximately 70% organic matter which consists of pollens, field dust, insect debris, mold spores, and grain fragments (US EPA, 2003). Due to their easily suspendible nature and high organic matter content, the concentration of grain dust beyond the minimum explosible concentration (45-150 g·m-3) poses an explosion hazard (Palmer, 1973; Noyes, 1998). The risk becomes bigger when the other components of the dust explosion pentagon which includes confinement, oxygen, heat source, and dispersion mechanism are satisfied. Grain dust also poses several health hazards to the people exposed to it. Various studies indicated that prolonged exposure to high grain dust concentration has caused eczema (Laraqui et al., 2003), asthma (Lachowsky & Lopez, 2001), allergic rhinitis (Ghosh, Gangopadhyay, & Das, 2014), and hypersensitivity pneumonitis (Skorska et al., 1998). The dust may contain bacteria and secondary metabolites such as mycotoxins and endotoxins which are deadly when inhaled or ingested (Halstensen et al., 2013).

Several studies throughout the years were conducted to minimize the hazards associated with grain dust. Explosion mitigation strategies such as automatic vents, chemical explosion suppression systems, and passive valves were created to prevent flame propagation when a primary explosion happens. The use of various dust collection systems such as cyclones, electrostatic dust collectors, and baghouses was established to lessen the amount of dust emitted to the atmosphere. However, despite all these strategies, grain dust still continues to become a huge problem. There is also a scarcity of publications that determine the different properties of dust like the complete range of particle size distribution, individual particle shape characteristics, flowability properties, and floodability properties which are critical in the design and modeling of dust emission mitigation strategies and facilities.

1.2 Research Objectives

This research focused on the characterization of select grain dust types and the influence of repeated handling in bucket elevators to the quantity and characteristics of dust produced. Listed below are the specific objectives of this study. The first two objectives are for the repeated handling study in Chapter 3 while the last two are for the flowability and floodability study in Chapter 4.

Specific Objectives

1. Examine the effect of soybean grade and elevator type on the particle size, particle size distribution (PSD), and shape characteristics of soybean dust emitted from repeated bucket elevator handling.
2. Determine and compare the quantity and characteristics of dust collected at different points in the bucket elevator.
3. Quantify the size, shape, flowability, and floodability characteristics of wheat, corn, soybean, rice, and milo dust.

4. Determine the influence of size and shape characteristics on the flowability and floodability of five grain dust types.

1.3 Outline

This manuscript is divided into four chapters excluding the current chapter. Chapter 2 provides a brief literature review of dust properties, factors that affect dust generation, overview of grain dust explosions and explosibility parameters. In Chapter 3, the shape characteristics and size distribution of soybean dust emitted during repeated handling in pilot-scale bucket elevator legs were discussed. Chapter 4 describes the influence of particle size, particle size distribution, and shape characteristics of rice, wheat, corn, soybean, and milo dust to their respective flowability and floodability properties. Lastly, the summary of findings of this research and recommendations based on the findings of this work were discussed in Chapter 5.

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Chapter 2 - Grain Dust Properties, Emission, and Explosion: Literature Review

2.1 Particulate Matter Definition and Classification

The United States Environmental Protection Agency (US EPA) (2007) defines particulate matter (PM) or particle pollution as a mixture of minute particles and vapor droplets dispersed in the atmosphere. These particles often fall in the microscopic scale category and become visible only when present as clusters or aggregates. Particulate matter varies in shapes and sizes and may consist of dust, soot, dirt, and smoke emitted from various sources. Collectively, a system of particulate matter suspended in air is known as aerosols. Knowing the amount and concentration of PM is critical in the occupational and health settings since these particles could cause various respiratory-related diseases that interfere with worker's performance and efficiency.

PMs are classified based on median aerodynamic diameter (MAD), a value of aerodynamic diameter (AD) for which half of the particles are smaller than the MAD, and the other half is larger than the MAD. The American Conference of Governmental and Industrial Hygienists (ACGIH, 1997) classified PM into three categories based on health-related problems they cause: (1) inhalable fraction (PM with MAD of 100 µm that can enter the airways); (2) thoracic fraction (PM with MAD of 10 µm that penetrate parts of tracheal and bronchial regions); and (3) respirable fraction (PM with MAD of 4 µm that can deposit into the gas exchange regions of the lungs). Meanwhile, the US EPA (2007) regulates two particulate fractions: (1) PM_{10} (inhalable PM with $MAD \leq 10$ µm), and (2) $PM_{2.5}$ (fine inhalable PM with $MAD \leq 2.5$ µm).

The particle size distribution (PSD) of PM dispersed in the atmosphere can range from nanometer to micrometer scale. Based on average mass and composition, these particles fall into two general categories – coarse and fine. Fine PM are particles with AD less than 2.5 µm while coarse PM are particles with AD greater than 2.5 µm. The coarse particles are made up of materials that come from the earth's crust. These may be in the form of dust emitted from roads and constructions, residues of agricultural operations, and emissions from processing industries. Fine particles, on the other hand, originate from combustion and chemical processing industries that produce secondary aerosols and recondensed organic metal vapors (US EPA, 2007).

Classifying particulate matter based on aerodynamic properties is often more important than grouping them based on physical size alone. This is due to the fact that geometric size does not sufficiently describe the behavior of particles when suspended in the air. A more appropriate way is to express the particle size as aerodynamic particle diameter. This refers to the diameter of a hypothetical sphere with a density equal to that of water and settles in still air at a terminal velocity similar to the particle in question (WHO Regional Office for Europe, Copenhagen, and Denmark, 2000). Aerodynamic properties such as AD help researchers determine the behavior of particles during handling and processing operations. Thorough understanding of these properties improves effectivity of pollution control systems in removing PM from different gaseous mediums. In addition, the aerodynamic behavior relates the chemical characteristics of the particles to the origin of emission, which is highly beneficial in air pollution studies (WHO Regional Office for Europe, Copenhagen, and Denmark, 2000).

2.2 Grain Dust Definition and Classification

While particulate matter is clearly defined in many publications, the definition of dust is often ambiguous. There are two standard dust definitions that are commonly used in occupational hazard analysis. The first describes dust as small solid particles with diameters of 75 µm or less and settle out under their own weight after being suspended in the air for some time (International Standardization Organization [ISO], 1995). The second describes dust as a small solid particle emitted into the atmosphere by man-made (e.g., mechanical crushing, shoveling, demolition, screening, sweeping, drilling, and milling) or natural processes (e.g., wind and volcanic eruption) and settles slowly due to gravitational force (International Union of Pure and Applied Chemistry [IUPAC], 1990). By contrast, the latter definition limits the range of dust particle size between 75 to100 µm.

The primary sources of dust emission in agriculture are field operations (e.g., bed preparation, soil tillage, crop planting, pesticide and fertilizer application, harvesting, storage) and post-harvest processes (e.g., cleaning, drying, cooking, crop modification). Dusts emitted from these activities consist mainly of soil particles, dirt, fungal spores, and small remnants of weeds and other plant parts. In livestock and poultry production, the generation of dust is affected by factors such as animal bedding, activity and type, stocking density, housing ventilation rate, and feeding methods (Jager, 2005). Livestock dust typically consists of soil particles, bedding materials, feeds, litter, and fecal matter (Guarino, Jacobson, & Janni, 2007).

Grain dust is another type of agricultural dust generated by moving and transferring large quantities of grains in handling facilities such as bucket elevators, silos, conveyor belts, and grain dryers. The dust accumulates on the surface of the grains during harvesting and transport, and disperses into the atmosphere when the grains are processed in commercial establishments. The quantity and rate of dust emission are affected by the grains' inherent dustiness and the mechanical forces, like abrasion and attrition, applied to the grain (Billate, Maghirang, & Casada, 2004). Grain dust consists of approximately 70% organic materials, 15% free silica, and small percentages of hulls, field dust, pollens, insect debris, soil particles, and fungal spores (US

EPA, 2003). This composition varies depending on the environmental conditions, types of grain, and methods of handling.

2.3 Studies on Particle Size Distribution

Although generally perceived as small entities, grain dust varies largely in size and shape. The differences in the fraction of particle sizes determine the extent of hazard the dust poses. For instance, a sample volume of dust containing more than 80% of $PM_{2.5}$ is more likely to cause severe respiratory ailments than a sample volume containing 80% PM_{10}. In determining the PSD of small particles, the volume standard is the most common dimension used, but other standards like area, length, and quantity may also be utilized.

As early as the 1970s, studies on the PSD of dust generated from handling of various grains were already published. However, since PSD is significantly affected by grain class and type of handling methods, complete PSD data for primary grain crops like wheat, rice, sorghum, and milo are still scarce. The PSD of dust emitted from internal and external processing units in grain handling facilities, especially in grain elevators, are also limited. Based on the report published by US EPA (2004), roughly 25% of the total dust generated from grain handling operations constitute PM_{10}, while approximately 17% consists of $PM_{2.5}$. For both exports and country elevators, handling of wheat generates an average PM_{10} of 30%, while handling of soybean and corn generates PM_{10} of at most 30% of the total dust (Midwest Research Institute, 1998).

Dust emission sources include internal and external processing operations in grain handling facilities. For receiving activities, the PM emission ranges from 8.3 to 90.0 g/t of grain (Kenkel & Noyes, 1995; Midwest Research Institute, 1998; Shaw, Buharivala, Parnell, & Demny, 1998; US EPA, 2003; Billate et al., 2004). These include unloading from ships, railcars, hopper- and straight-bottom trucks, and barges. For grain cleaning operations involving internal vibration and cyclone, the total PM emission is roughly 37.5 g/t of grain. From this, 9.50 g/t constitutes PM_{10}, while 1.60 g/t constitutes $PM_{2.5}$. Dust emissions from internal handling (e.g., scales, belts, legs, and distributors) and headhouse are slightly lower than that of the receiving and cleaning operations with 30.5 g/t of grain. Meanwhile, storage vents generate the lowest amount of dust at 12.5 g/t of grain. The vents also emit the lowest fractions of $PM_{2.5}$ and PM_{10} (Midwest Research Institute, 1998; US EPA, 2003). Kenkel and Noyes (1995) reported the total PM collected from grain shipping (ships, railcars, barges, trucks) and drying operations (racks and column dryers) ranged from 4.0-43.0 g/t and 110-1500 g/t of grain, respectively.

Grain types also affect the particle size distribution of grain dust emissions. Parnell, Jones, Rutherford, and Goforth (1986) made one of the most comprehensive studies covering five grain dust types (soybean, rice, wheat, corn, and sorghum). However, they limited their observation to dust fractions with particle size of at most 100 µm. The median particle size of the dust particles was reported to be 13.6 µm for soybeans, 10.7 µm for rice, 13.2 µm for corn, 13.4 µm for wheat, and 14.0 µm for sorghum. Martin and Lai (1978) reported the average percentages of residual dust belonging to PM_{10} to be roughly 45%, 33%, and 34% for wheat, corn, and sorghum, respectively. For wheat, the average mass median diameter of the dust that clings to the kernels and small fragments is 13 µm. Piacitelli and Jones (1992) studied the PSD of sorghum dust generated from on-farm handling processes that include on-farm storage, harvesting, and grain transport. They found out that 52% of the particles have an AD of more than 21 µm. The percentages of other fractions, including those that have ADs of $\leq$3.5 µm, $\leq$10 µm, and $\leq$15 µm, were 2%, 10%, and 24%, respectively.

The most recent study about the particle size distribution of grain dust was that of Boac, Maghirang, Casada, Wilson, and Yung (2009). They reported an average wheat dust %PM of 5.15, 9.65, and 33.6 for $PM_{2.5}$, PM_4, and PM_{10}, respectively. For corn dust, the mean %PM for the lower and upper ducts of the bucket elevator were found to be 7.46, 9.99, and 28.9 for $PM_{2.5}$, PM_4, and PM_{10}, respectively. The shelled yellow dent corn produced a greater fraction of small particles than wheat. Furthermore, the PSD of the dust collected from the lower and upper ducts of the bucket elevator showed insignificant differences among repeated transfers and grain lots but varied between ducts and grain lots.

2.4 Workplace Emissions and Health Concerns

Respiratory-related diseases are the primary health hazard attributed to grain dust exposure and inhalation. Despite a plethora of publications that determine how various grain dust types cause disruption in the human respiratory system, grain-dust related complications are hard to characterize precisely due to several factors. These include the complex properties and composition of the dust, vast array of clinical diseases the dust causes, differences in the extent of exposure and inhalation, microscopic pathogenic materials present in the dust, and the continually changing patterns of illness with reduced exposure (Chan-Yeung, Enarson, & Kennedy, 1992).

The severity of dust exposure depends on the nature of job the workers are situated into. On-farm workers are exposed to high dust concentrations during planting, cleaning, transferring, and harvesting of grains, while elevator operators experience the highest exposure during bulk transport and bagging of grains. The number of grain elevator workers in the United States is estimated to be more than 100,000 while the number of on-farm workers is even higher, especially in tropical and subtropical regions (Chan-Yeung et al., 1992). Hence, the potential health impact of dust inhalation is enormous.

Various studies indicated that prolonged exposure to high grain dust concentration has caused eczema (Laraqui et al., 2003), asthma (Lachowsky & Lopez, 2001), allergic rhinitis (Ghosh, Gangopadhyay, & Das 2014), and hypersensitivity pneumonitis (Skorska et al., 1998) Chan-Yeung et al. (1992) reported the release of histamine, a compound involved in the inflammatory response, from rat peritoneal mast cells upon addition of grain dust extracts. These extracts can trigger the harmful release of leukotrienes B4, D4, and E4 from human lung fragments when exposed to sufficient doses. Olenchock, Mull, and Major (1980) also observed that grain dust extracts could stimulate the proliferation of lymphocytes which is an indication of an on-going infection. Aside from inherent properties of grain dust, it is also likely that the diseases associated with it are caused by contaminants adhering on its surface (Von Essen, 1997; Skorska et al., 1998; Douwes, Thorne, Pearce, & Heederik, 2003). Fungi like *Penicillium* and *Aspergillum* may be present in the dust due to long-term storage in bins and silos (Dacarro et al., 2005). The dust may also contain bacteria and secondary metabolites such as mycotoxins (e.g., Aflatoxin, Fusarium, and Trichothecene) and endotoxins (Halstensen et al., 2013).

There are also several publications that address the occupational factors related to dust exposure in grain industries. Most of these studies were undertaken in North America and Europe while a few were conducted in some parts of Central and South America (Halstensen et al., 2007). Straumfors, Heldal, Wouters, and Eduard (2015) found out that workers of cleaning and process control operations experience higher levels of exposure than those involved in inspection, driving, packing, and laboratory works. In the farm setting, Halstensen et al. (2007) observed higher dust exposure levels for workers involved in grain storage than in harvesting and threshing. Rodriguez-Zamora et al. (2017) reported a grain storage facility in Costa Rica where the personal inhalable dust concentration exceeded the international exposure limits. They observed that corn and wheat storage facilities, as well as drying and unloading areas have the highest concentration of thoracic dust fraction (PM_{10}). The results were higher than the observed inhalable dust concentration from animal feed mills and grain elevators in Norway (Straumfors et al., 2015). The National Institute for Occupational Safety and Health (NIOSH, 2011) regulates an 8-hour time-weighted average limit of 10 mg/mg^3 for oats, wheat, and barley dust, measured as total dust. For other grain types, the regulated PM dust emission is 15 mg/mg^3 and a respirable fraction ($PM_{2.5}$) of 5 mg/mg^3. NIOSH stated that these limits significantly reduce the risk of having chronic respiratory illnesses.

2.5 Grain Handling and Dust Emissions in Receiving Areas

Grain receiving areas are often identified as the most critical areas for dust control. Cereal grains from fields and storage systems are unloaded using trucks or railcars into these areas. The process of unloading grains generates dust particles that are immediately emitted to the atmosphere. Air is displaced as grains fall into the pit, which creates a turbulent mixture of air and dust (Midwest Research Institute, 1998). Another source of PM is the transfer of grains from elevators to trucks and railcars. During this process, grain flow from the storage bin into the truck bin is influenced by gravity. According to Billate et al. (2004), the amount of dust generation is dependent on several factors such as grain flow rate, type, and quality, drop height, degree of enclosure, moisture content, and the efficiency of dust collection system installed in the area.

A truck dumping platform is commonly used in country elevators for unloading grains from straight bottom trucks. For trucks with hopper-type bottoms, grains are directly discharged to the pit without the need for a dumping platform. The receiving area of grain elevators is designed so that the truck can drive to a tunnel equipped with a roll-down door on one or both ends for easy entrance and exit. During unloading, the wind may enter the tunnel at speeds larger than those in the open areas. These wind currents accelerate the dispersion of dust and expose the operator to a dust-laden air. As a solution, grain facilities are constructed against the direction of the prevailing wind and installed with a roll-down or bi-fold openings to mitigate the effects brought by the wind. Moreover, a shed around the hopper discharge is sometimes built to minimize the effect of wind currents to the rate of dust emission.

Unloading areas are made up of heavy grates where the grains can freely pass as they fall into the receiving pit. This pit is always partially filled with grains since the speed of the conveyor belt that transfers the grain from the storage pit to the elevator is less than the speed at which the grains enter the receiving pit. To minimize dust generation, hopper trucks and railcars are installed with choke-flow structures with choke unloading mechanism which cause the material to form a cone around the receiving grate (US EPA, 2004).

Majority of grain handling facilities install dust capture systems at the receiving pits to bring down dust emission levels to tolerable quantity (Wallace, 2000). Billate et al. (2004) reported that these collection systems are designed to remove a quantity of air that equates the volume of entrained air and the volume displaced by the incoming mass of grain. A few studies on air entrainment in bulk materials and industrial powders (Dennis & Bubenick, 1983; Hemeon, 1963; Cooper & Arnold, 1995; Plinke, Leith, Boundy, Loffler, 1995) are available in literature. There are also some published data on the quantity of dust emitted in grain receiving areas but without specific emphasis on the complete particle size distribution of dust (Wallace, 2000).

Kenkel and Noyes (1995) reported a 19.4 g/t and 9.5 g/t emission of airborne dust from wheat handling in the receiving area of a country elevator using a straight- and hopper-bottom truck, respectively. Shaw et al. (1998) observed an average corn dust emission rate of 8.5 g/t in receiving operations of three feed mills in cattle feed yard. The Midwest Research Institute (1998) also published particulate emission rates in receiving operations for both terminal and country elevators. They reported an average dust emission rate of 16 g/t and 150 g/t for hopper- and straight-truck receiving, respectively. Billate et al. (2004) studied PM emissions from the receiving operations of corn using simulated hopper-bottom trucks. They observed that the emission rate of total suspended particulates (TSP) and PM_{10} decreased when both the drop height and grain flow rate are lowered. PM_{10} emission rates ranged from 0.6 to 6.1 g/t of corn, while TSP emission rates ranged from 8.3 to 14.6 g/t of corn.

2.6 Grain Handling and Dust Emissions in Grain Elevators

Two types of elevators are commonly used in grain storage facilities - country and terminal elevators. Terminal elevators are large-scale elevators that dry, clean, blend, and store grains before transport to other terminals or processors. These elevators have large storage and handling capacities and receive grains by truck, rail, or barge. When terminal elevators are used to load grains onto ships for export to other countries, they are called export elevators. Meanwhile, a smaller type of elevator commonly found in small grain storage and processing facilities is the country elevator. It can receive grains from the truck directly from the farm or another storage during the harvest period. In some facilities, grains are initially cleaned and dried in the country elevators before they are transferred to terminal elevators for further processing.

The flow of grains in a grain elevator begins when an incoming truck or railcar discharges the grains into a receiving pit typically found below the ground. For barges, a bucket elevator with legs extended into the barge hold is utilized. From the hopper, grains are conveyed into the main building of the elevator called the headhouse. This is where grains are lifted on one of the elevator legs using buckets and discharges them into different silos or storage bins. During storage, grains can be transferred to a different bin or may be emptied from the bin using enclosed conveyors, direct spouting, augers, and screw conveyors.

The US EPA (2003) cited two potential PM emission sources in a grain elevator system – external emission sources and process emission sources. External sources involve the areas in grain receiving and shipping where particulate matter is emitted directly from the operations to the atmosphere. These operations are typically employed outside the elevator enclosures but within partial enclosures and are affected by the localized wind currents present within the area. Process emission sources, on the other hand, include operations conducted in the headhouse such as grain cleaning and internal handling. Parts of the elevators like the elevator legs, buckets, tunnel belts, and distributor also contributes to the amount of emitted dust. Some elevators are equipped with an aspiration system where particulate matter is collected through filters and cyclones before the stream of air is discharged out of the system. When aspiration systems are absent, the amount of dust emitted to the atmosphere is dependent on the enclosure tightness and internal elevator housekeeping practices.

Parnell et al. (1986) reported percentages of five grain dust types with particle size less than 100μm. The results were 54.1, 34.3, 44.2, and 50.6% PM dust of the total dust collected for corn, wheat, sorghum, rice, and soybean, respectively. Meanwhile, Boac et al. (2009) studied the complete PSD of dust emitted from the handling of shelled corn and wheat in grain elevators, focusing on PM_{10} for regulatory concerns and PM_4 for health concerns. They found out that the geometric mean diameter (GMD) ranged from 10.0 to 14.4 µm and 10.5 to 16.9 µm for corn and wheat, respectively. The wheat produced a higher proportion of larger particles compared to the shelled corn. The PSD during the transfer operation was approximately 29%, 10%, and 7% of the total shelled corn dust for PM_{10}, PM_4, and $PM_{2.5}$, respectively. For wheat, a higher percentage of PM_{10} was observed. Of the two grain types, shelled corn generated twice the amount of dust produced by wheat since its inherent dustiness is greater (Parnell et al., 1986; Martin & Lai, 1978; Martin & Sauer, 1976). In addition, corn has a weaker structural composition, which makes it susceptible to breakage during handling in grain elevators (Fiscus et al., 1971). The complete particle size distribution published by other sources are presented in Table 2.1.

Table 2.1 Particle size distribution of various grain dusts from grain elevators

Grain Type	Percentage PM Dust of the Total Dust Collected (%)					
	<125 µm	<100 µm	<10 µm	<8 µm	<4 µm	<2.5 µm
Wheat	33.0-78.0[a,c]	34.3[f]	33.6[h]	3.00-4.00[a]	9.65[h]	5.15[h]
Corn	62.0-86.0[a,b,c]	54.1[f]	5.00-28.9[e,g,h]	5.00-12.00[a]	0.60-9.99[g,h]	0.20-7.46[g,h]
Sorghum	60[c]	34.3[f]	-	-	-	-
Rice	-	44.2[f]	-	-	-	-
Soybean	-	50.6[f]	-	-	-	-

[a] Martin and Sauer, 1976 (from table 2)
[b] Martin and Stephens, 1977 (from table 1)
[c] Martin and Lai, 1978 (from table 3)
[d] Martin, 1981 (interpolated from figure 5 by Boac et al. (2009))
[e] Lai et al., 1984 (interpolated from figure 5 by Boac et al. (2009))
[f] Parnell et al., 1986 (from table 3)
[g] Baker et al., 1986 (interpolated from figure 2 by Boac et al. (2009))
[h] Boac et al., 2009 (from table 6)

The quantity of dust emitted from grain elevators depends on grain type, quality and moisture content, speed of belt conveyors, and efficiency of dust collection and containment system installed (US EPA, 2003). Terminal elevators, in general, produce larger amounts of dust since unloading is done throughout the year. For country elevators, grain unloading declines after harvest season and becomes non-existent throughout the rest of the year until another harvest period occurs.

2.7 Repeated Handling of Grains

The transfer of grains to and from storage bins and grain elevators accelerates dust emission to the atmosphere as frictional forces between grains and bin walls impact the surface of the grains. As of writing, very few studies have addressed the effect of repeated transfers on the quantity and quality of dust produced by different grains. Martin and Stephens (1977) investigated the effect of repeated transfers on dry shelled corn by transferring grains across two bins 20 times. Their results indicated that the amount of accumulated breakage in the corn increased by 0.6% for each transfer from one container to another. From 2%, the level of breakage rose to 15.7% after the last transfer. The mean amount of dust generated for every transfer of corn was 0.088% of the dry corn weight. The fraction of particles less than 125 μm decreased slightly during repeated handling, but more than 70% of the emitted dust passed through a 120-mesh sieve (fine dust). The flow characteristics of grain for repeated handling can affect the amount of breakage, and the amount of dust produced. However, the emission of fine fractions became constant after the initial buildup and despite the overall increase in breakage (Martin & Stephens, 1977).

Converse and Eckhoff (1989) also studied the emission of corn dust with repeated elevator transfers as affected by different drying treatments. They found out that the amount of dust emission, determined by the weight of dust captured by the pneumatic dust control system, did not change drastically throughout the entire transfer-impact test within a given test lot.

However, the cumulative amount of fine dust (≤120 μm) and the rate of dust emission were observed to have a positive correlation with the number of repeated transfers in the concrete elevator, severity of heated air-drying treatment, and degree of over-drying. This explains why corn lots that have been exposed and dried to air temperatures ranging from 100°C to 105°C emitted the highest amount of dust.

The most recent study concerning the effect of repeated handling in dust generation was that of Boac et al. (2009). Using shelled yellow dent corn, they performed eight bin transfers with a mean material flow rate of approximately 57 tons/h, a mean mass of 25.3 tons, and an initial grain drop height of 26 meters. The results of the experiments revealed that the GMD and GSD of the dust were not significantly different. Also, the particle size distribution showed insignificant differences among repeated transfers. Parnell et al. (1986) stated that the variations in the results could be explained by the differences in grain properties, sampling methods, measurements, and grain elevator operation.

2.8 Effect of Grain Type on Dust Generation

Due to the inherent properties of different grain types, the quality and amount of dust produced during handling also vary (Boac et al., 2009; Parnell et al., 1986; Martin and Sauer, 1976). The common physical properties used to characterize the dust particles include size, shape, density, and surface area (Martin, 1981), but various researchers have focused on the PSD to determine the fractions that pose health and explosion hazard. Determining the differences among grain dust properties is critical since a dust control system may not be useful in the mitigation of hazards produced by another type of dust.

Parnell et al. (1986) comprehensively studied the physical properties of the dust from soybean, rice, corn, wheat, and sorghum collected from terminal elevators. Table 2 summarizes these values along with data from Wade et al. (1979), Plemons (1981), Martin (1981), and Plemons and Parnell (1981). The table shows sorghum with the largest mean mass diameter and bulk density, while corn has the smallest mean mass diameter, bulk density, and ash content. Plemons (1981) and Martin (1981) performed the particle characterization by wet sieving, dry sieving, and Coulter counter techniques while Wade et al. (1979) only performed Coulter counter for particle size distribution. The surface areas of the dust were measured using adsorption techniques and light obscuration methods (Martin, 1981), while the particle densities were measured using a Beckman air pycnometer (Parnell et al., 1986).

Table 2.2 Published physical properties of common dust types from grain elevators

Grain Type	Mass mean diameter (µm)	Particle Density (g/cm^3)	Bulk Density (g/cm^3)	Surface Area (m^2/g)	Ash Content (Dry Basis), %
Wheat	32.97[b]	1.48[e]	0.208[e]	0.862[e]	7.19-28.5[c,e]
Corn	13.70-19.57[a,b]	1.50[e]	0.153[e]	0.826[e]	1.88-12.0[c,d,e]
Rice	21.75[b]	1.46[e]	0.22[e]	1.092[e]	30.6-31.45[d,e]
Sorghum	36.92[b]	1.43[e]	0.308[e]	0.866[e]	7.5-9.59[d,e]
Soybean	15.50-30.00[a,b,c]	1.69[e]	0.150[e]	0.869[e]	12.1-40.5[c,d,e]

[a] Wade et al. (1979) (from table 1 of Parnell et al. (1986))
[b] Plemons (1981) (from table 1 of Parnell et al. (1986))
[c] Martin (from table 1 of Parnell et al. (1986))
[d] Plemons and Parnell (from table of Parnell et al. (1986))
[e] Parnell et al. (1986) (from tables 4, 5, and 7)

Very few studies have investigated the thermal properties of grain dust, such as specific heat and bulk thermal conductivity. Chang (1986) reported that the thermal conductivities of corn dust, grain sorghum dust, and wheat dust increased linearly with bulk density and moisture content. At densities ranging from 240 to 580 kg/m^3 and moisture content (w.b.) ranging from roughly 8% to 17%, the thermal conductivities ranged from 0.086 to 0.101 W/(m-°C), from 0.08 to 0.09 W/(m-°C), and from 0.062 to 0.074 W/(m-°C), for corn dust, grain sorghum dust, and wheat dust, respectively. The specific heat of the three dusts increased linearly with increasing moisture content and has a value ranging from 1900 to 2200 J/(kg-°C).

In terms of the quantity of dust produced during handling, Martin and Sauer (1976) and Martin and Lai (1978) both reported that corn significantly generated a larger amount of dust than wheat. This was similarly observed by Boac et al. (2009) when the yellow-dent corn generated more than twice the amount of dust produced by wheat upon handling in a grain elevator. The corn produced 185 grams of dust per ton of corn handled while the wheat generated roughly 65 grams of dust per ton of wheat handled.

The inherent dustiness of the grains also affects the quantity of dust the grains produced. Martin & Lai (1978) reported corn, sorghum, and wheat to have different dustiness characteristics since coated grains tend to retain more residual dust (fine dusts that cling to kernels and fragment). Upon extraction of the residual dust, they reported that the residual dustiness levels were significantly higher in corn than in either sorghum or wheat samples. In addition, the percentage of the residual dustiness for corn and wheat was approximately equal to the percentage of fine dust (particles that pass through 120-mesh) collected from the grains during handling. An earlier study conducted by Martin and Sauer (1976) defined relative grain dustiness as the "*total weight of cyclone tailing dust, expressed as a percentage of the weight of the grain*.". They reported that both handling operation and grain type affected dustiness characteristic of grain.

2.9 Grain Dust Explosion

2.9.1 Brief History of Occurrence

Although dust explosion phenomena may have occurred several centuries earlier, the first recorded incident happened in 1785 when a mounted lamp ignited the flour dust inside the Giacomelli's Bakery Warehouse in Italy. A follow-up investigation revealed that the explosion of dry flour dust had caused more destruction than common fire. In the United States, several investigations were made to evaluate the explosibility of combustible dust and causes of rising dust explosion incidents in flour mills. This led to the formation of the National Fire Protection Association in 1896, which recognized the risks and hazards associated with the handling of explosible dust (Verakis & Nagy, 1987).

The number of dust explosion in the US has gradually fallen in the last 40 years (OSHA, 2016). An annual average of 21.7 explosions was recorded from 1976 to 1985, with 44 injuries and 14 deaths. These numbers dropped to 13.8 explosions from 1986 to 1995, 12.6 from 1996 to 2005, and 9.7 from 2006 to 2014. Sanghi and Ambrose (2016) reported that within the 2006-2014 timeframe, 67.8% of incidents have unknown ignition source. Fire has caused only 6% of the total incidents, while welding and friction sparks have caused only 3.6%. The number of incidents caused by other ignition sources is presented in Table 2.3.

Table 2.3 Ignition source of agricultural dust explosions (Sanghi and Ambrose, 2016).

Ignition source	Number of incidents	% of incidents
Unknown	57	67.8
Fire	5	6
Welding	3	3.6
Friction sparks	3	3.6
Malfunctioning mechanical components	2	2.4
Smoldering material	2	2.4
Overheated bearing	2	2.4
Spark from electrical equipment	2	2.4
Exposed light fixture	2	2.4
Spark in the dust collection unit	1	1.2
Spark in dryer	1	1.2
Dust collector malfunction	1	1.2
Malfunctioning pulley	1	1.2
Lightning strike	1	1.2
Structural collapse	1	1.2
Total	84	100

2.9.2 Combustible Dust and Formation of Dust Cloud

Combustible dust is any solid material consisting of discrete units or particles, that presents a fire hazard when suspended in an oxidizing medium regardless of chemical composition, shape, and size (OSHA, 2016). Any material falling under this definition can become combustible under specific situations. Frank (2004) listed several commodities that have caused explosion incidences in various industries throughout the years. These include wood and paper dust from woodworking; grain dust and flour from grain processing and storage; metallic dusts from metal processing; pulverized coal and peat from power generation; pharmaceuticals, dyes, and acetate flakes from chemical process industries; sulfide ores, coal, and sulfur from mining activities; and plastics from polymer industries. Grain dust is a highly combustible material. Due to its small particle size, the potential combustion energy it can release is higher than that of coal. When dust emission and accumulation is not regulated, the associated explosion risk and immediate danger to human lives and properties are enormous.

2.9.3 Dust Explosion Pentagon

Understanding how dust explosions occur requires the fundamental concept of the fire triangle. Figure 2.1 shows the three critical requirements to start a fire - fuel, oxidant, and an ignition source. If at least one component is absent, a fire will not start. Kauffman (1982) extended the basic fire triangle into an explosion pentagon by adding the mixture of fuel and oxidant, and confinement where the mixing occurs. However, the mixing process applies mostly to gaseous explosions rather than dusts. In a gas explosion, the smallest particles of fuel and air have negligible gravitational effects and are separated from each other by molecular distances, making the mixing process readily available (Amyotte & Eckhoff, 2010). In a dust explosion, on the other hand, most of the dust particles are large enough to be influenced by gravitational forces, hence a dispersion mechanism is necessary.

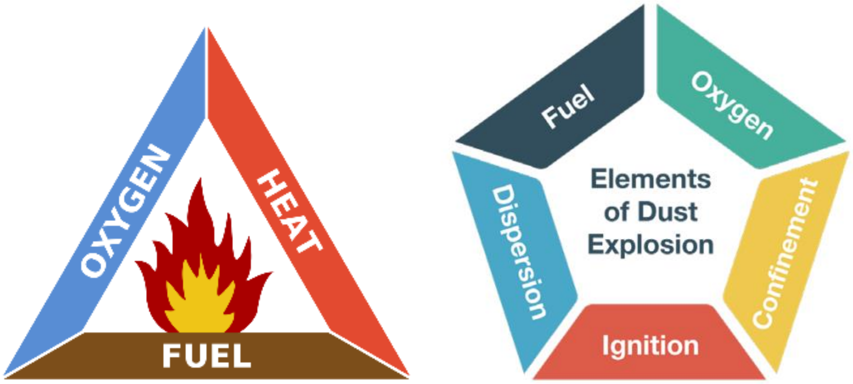

Figure 2.1 Fire triangle (left) and dust explosion pentagon (right)

Dust particles of primary grain crops like wheat, rice, corn, barley, or fine powders such as wheat flour, corn starch, and wood dust fall under the category of combustible dust. According to Birtwistle (2003), dust particles with diameters of at most 400 μm are most likely to cause an explosion. Common sources of ignition include overheated bearings in conveyors, heads, and elevator leg boots, static electricity and electrostatic discharge, mechanical friction between sidewall casing and elevator leg belts, electrical arcs and shorts from equipment unequipped with explosion devices, exploding tablets or pellets of phosphine in a wet aeration duct, burning cigars from cigarette smoking, welding and cutting torches, malfunctioning mechanical components such as pulley and dust collector, exposed light fixtures, smoldering materials, metal sparks from grinders and other electrical equipment, metal to metal sparks, lightning strike, dropped tools, and structural collapse (Sanghi & Ambrose, 2016). Typical confinement types, on the other hand, include vertical leg of a bucket elevator, downspout, dust bin, enclosed drag conveyor, aeration duct, basement tunnel, and silos.

2.9.4 Primary and Secondary Explosions

Dust explosion happens in two successive stages – primary and secondary. A primary explosion begins in one or more process units inside a processing building like a grain elevator, a filter unit, or a mill. When dust is confined in one of these units and heated at a temperature that permits combustion, a primary explosion takes place. The explosion releases an initial shockwave that disperses dust in adjacent areas, which creates a secondary cloud of dust. When this cloud ignites, a more energetic secondary explosion takes place. The dust flame travels outward and moves at a swift rate, building a bigger flame and creating another shockwave that disperses more dust and triggers stronger explosions. Given favorable conditions, a secondary explosion often follows a primary explosion and causes more destruction. Eckhoff (2019) reported that a gap of about two orders of magnitude between the bulk density of dust layer and maximum explosive dust concentration exists. This means that for a commonly used dust collection duct with a tube diameter of 20 cm, a 0.01 mm layer of dust with a bulk density of 500 kg/m^3 is enough to produce a dust cloud with a concentration of roughly 1000 g/m^3. This presents a larger hazard when a secondary dust explosion happens in process plants.

Not all secondary explosions result in destructive explosions. When a secondary flame created by the dust cloud creates a pressure rise large enough so that the building or containment cannot tolerate the pressure anymore, a typical explosion accompanied by an audible “bang” and destruction of structures happen. However, when the combustion of the secondary cloud does not create enough pressure rise, dust cloud flash fire occurs. The fast blast wave created by the primary explosion carries and disperses the dust particles into immediate areas, and the flame from the primary explosion burns the suspension in a split second. Although less destructive than explosions, flash fires can travel into long distances until there is no dust cloud suspension left in the area. The fires may reach a very high temperature that can cause severe burns and death. In addition, the resulting smoke can bring severe impairment to the tissues of the lungs when inhaled (Eckhoff, 2019).

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Chapter 3 - Size distribution and shape characteristics of grain dust emitted during repeated handling in pilot-scale bucket elevator legs

Abstract

Moving and transferring grains in large quantities generate grain dust that poses both health and safety hazards. In this study, two pilot-scale bucket elevator legs with different feeding directions [front-feed (FF) and back-feed (BF)] were used to examine the effect of repeated handling on the soybean dust quantity, particle size (circle equivalent diameter), and size distribution (PSD), and shape characteristics (high sensitivity circularity, aspect ratio, and elongation). The effect of soybean grades [1 (G1) and 3 (G3)] and elevator types on various parameters was also studied. The dust samples were collected at different points of the bucket elevator using glass fiber filters with cassette assembly and an air sampling pump. The filters were conditioned in a constant humidity chamber before and after sampling to minimize the effect of humidity on the filter mass. Particle size and shape analysis were conducted via 2D imaging in the Malvern Morphologi G3 SE. Results showed significant differences ($p<0.05$) in the mass of dust collected (m_d) among soybean grades and elevator types only in the first transfer while no significant differences ($p>0.05$) in the m_d were observed in the last transfer. A general decreasing trend in the quantity of dust collected was also observed for all elevator types and soybean grades. The circle equivalent diameter of the dust particles ranged from 3.00 µm to 8.36 µm. The overall PSD across grades, runs, and sampling points did not significantly vary ($p>0.05$). The measured values of HS circularity, AR, elongation, solidity, and convexity ranged from 0.70 to 0.84, 0.65 to 0.73, 0.27 to 0.35, 0.92 to 0.98, and 0.95 to 0.99, respectively. Significantly higher ($p<0.05$) PM_{10} percentage (88.39%) during 21st run was observed for G1 soybean dust generated as compared to its 1st run both at S2 and S3 of FF elevator. Moreover, G3 soybeans generated a significantly higher ($p<0.05$) PM_{10} percentage of dust at S3 during the 21st run (92.52%) as compared to the 9th run.

Keywords: repeated handling, grain dust, grain elevator, soybean, particle size distribution

3.1 Introduction

Handling of grains in bucket elevator generates fugitive dust emissions that can cause both health and safety issues. These emissions are usually composed of particulate matter (PM) that are characterized based on median aerodynamic diameter (MAD). The American Conference of Governmental and Industrial Hygienists (ACGIH, 1997) has classified particulate mass fractions that are significant in addressing health concerns related to dust inhalation – respirable fraction (PM with MAD of 4 µm that enters the gas exchange regions), thoracic fraction (PM with MAD of 10 µm that deposits in the tracheobronchial region), and inhalable fraction (PM with MAD of 100 µm that enters the airways). Meanwhile, the United States Environmental Protection Agency (US EPA, 2007) regulates two particulate matter fractions that are critical in air pollution studies – PM_{10} (inhalable PM with MAD of at most 10 µm) and $PM_{2.5}$ (fine inhalable PM with MAD of at most 2.5 µm).

There are two types of elevators that are commonly used in grain handling centers – country and terminal elevators. Terminal elevators are large-scale elevators that dry, clean, blend, and store grains before transporting them to other terminals or processors. They have large handling capacities and receive grains by barge, rail, or truck. Country elevators, on the other hand, are smaller elevators used in small grain handling facilities. This type commonly receives grains directly from the farm or another storage during harvest. In most cases, the grains are initially cleaned and dried in country elevators first before transferring them to terminal elevators for further processing (US EPA, 2003). Potential particulate matter emission sources in grain elevators can be classified as either external or process emission sources. External sources include grain shipping and grain receiving where PM is directly released from grain handling operations into the atmosphere and are quickly dispersed by wind currents. Meanwhile, process emission sources include headhouse, grain cleaning, and internal handling operations that may or may not be vented to the atmosphere. Common dust emission points in internal operations include tunnel belts, elevator legs, scale bins, and transfer points (US EPA, 2003).

Repeated handling in grain elevators affect grain breakage and quality (Boac, Casada, & Maghirang, 2008). When grains are transferred from one storage bin to another using grain elevators, dust is produced as the impact and frictional forces between grains and walls scrape the surface of the grain and loosen up any dust or dirt. Very few studies have addressed the effect of repeated elevator transfers on the quality of grains and the quantity of dust produced. Martin and Stephens (1976) performed 20 transfers of dry shelled corn across two bins and found out that the accumulated breakage in the corn increased by 0.6% for each transfer. The mean amount of dust produced for every transfer was observed to be 0.088% of the dry corn weight. The fraction of particles less than 125 µm decreased slightly during repeated handling, but more than 70% of the recovered dust have sizes of at most 120 µm.

Converse and Eckhoff (1989) observed linear relationship between the amount of cumulative broken and fine materials to the number of transfers in concrete elevator. They determined the amount of dust emissions from the weight of the materials collected by the two pneumatic dust control systems. Although there was an increase in the broken corn and fine materials for every transfer period, no buildup or decrease in dust emissions were measured. Boac, Casada, and Maghirang (2008) investigated the effects of repeated elevator handling on feed pellet and corn durability. They observed a 0.38% average percent increase of corn breakage for the eight transfers elevator transfers. The average mass of dust removed per transfer of the pellets (0.069%) was not significantly different from that of shelled corn (0.061%). The study did not characterize the particle size and distribution of the dust produced per repeated handling, but it was observed that the mass of dust <0.125 mm for the corn was 66% of the total dust which was significantly different from that of feed pellets (50%).

In terms of determining the complete range of particle size distribution emitted in grain elevators, Parnell, Jones, Rutherford, and Goforth (1986) made one of the most comprehensive studies covering five grain dust types (soybean, rice, wheat, corn, and sorghum). However, they limited their observation to dust fractions with particle size of at most 100 µm. The median particle size of the dust particles was reported to be 13.6 µm for soybeans, 10.7 µm for rice, 13.2 µm for corn, 13.4 µm for wheat, and 14.0 µm for sorghum. Martin and Lai (1978) also reported mean mass diameters of residual dust which are 14 µm for sorghum and 13 µm for wheat. The mean percentages of residual dust that belongs under PM_{10} were 45%, 33%, and 34%, for wheat, corn, and sorghum, respectively. The most recent study about the rate of dust generation and size distribution of grain dust was that of Boac, Maghirang, Casada, Wilson, and Yung (2009). They observed that shelled corn produced significantly smaller dust particles and higher proportion of small particles than wheat. The geometric mean diameter (GMD) of wheat and corn dust were 10.5 to16.9 µm and 10.0 to 14.4 µm, respectively. In addition, the yellow dent corn produced twice as much dust as wheat, but the repeated transfers did not have any significant impact on the GMD of corn dust produced.

From the preceding sections, it is noticeable that only two grain dust types are highly studied – wheat dust and corn dust. Only Parnell et al. (1986) studied the physical properties and particle size distribution of soybean dust. A small number of research studies were conducted on the effect of repeated handling on size distribution. Until now, limited data exists on the complete range of particle size and shape characteristics (SC) of grain dust emitted during grain elevator handling despite the elevators being used as the primary feed and grain handling system in the U.S. Hence, the main goal of this study was to obtain the quantitative values of particle size, particle size distribution (PSD), and shape characteristics (circle equivalent diameter, circularity, convexity, elongation, aspect ratio, solidity) of soybean dust emitted during repeated handling in pilot-scale bucket elevator legs. It also aimed to compare the PSD and shape characteristics of the dust collected at various points on the bucket elevator, identify the points in the elevator where the highest dust generation takes place, and investigate the effects of elevator type and soybean grade on the quantity, PSD, and shape characteristics of soybeans dust.

3.2 Materials and Methods

3.2.1 Test Facility

Two pilot scale B3 bucket elevator legs (Universal Industries Inc., Cedar Falls, Iowa), located at the USDA-ARS, CGAHR, Manhattan, Kansas were used to repeatedly handle soybeans. The first is a front-feeding elevator where both hopper and discharge spout are aligned on one side. The second is a back-feeding elevator where the hopper and discharge spout are located on opposite sides of the elevator. Both elevators have an enclosed base called boot where residual grains accumulate after initial material loading and during elevator operation. Based on the manufacturer's data, the elevators have handling capacities of 6 $t \cdot h^{-1}$ at 75% bucket filling. The metal covers of the two elevators were replaced with plexiglass to allow visual observation of grain flow and dust emission activity. In addition, a sliding gate was added to the hopper base to restrict the flow of soybeans and maintain the average soybean mass flow rate to 30 kg · min^{-1} (about 33% of the full leg capacity) with 20% hopper opening.

3.2.2 Grain Procurement and Preparation

Approximately 5000 lbs (2500 lbs for each lot) of soybeans were procured from Farmer's Cooperative Association, Manhattan, Kansas at two different times of the year. The first lot consists of U.S. No. 1 grade soybeans with 1.2% foreign materials (FM) and 0.5% damaged kernels (DK) while the second lot consists of U.S. No. 3 grade soybeans with 2.5% FM and 2.0% DK. The soybeans were loaded in a stainless-steel barrel with average weights of 155.0 kg per barrel. The initial and final moisture contents of the soybeans were determined by drying 15 g of samples in an air oven at 130°C for 72 hours (ASAE S352.2). Meanwhile, the test weight was determined using Seedburo Grain Tester (Seedburo GAC2500UGMA Dickey-John GAC 2500-UGMA Commercial NTEP Grain Tester, state, U.S.A.).

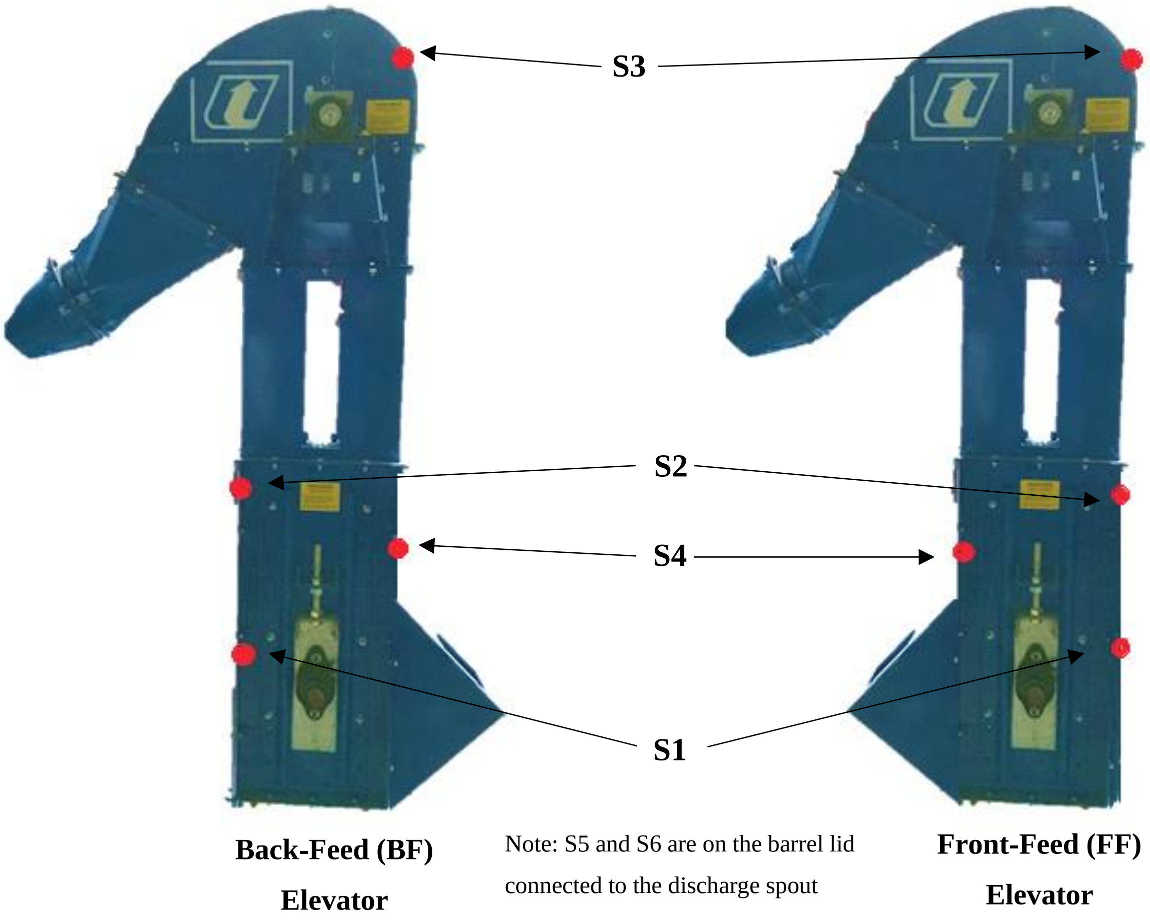
3.2.3 Preparation of Air Samplers

Two-piece air sampling cassettes (diameter = 37 mm) commonly used for personal air sampling were used to collect the dust samples inside the elevator leg. The cassette assembly consisting of a support pad, glass fiber filter (934-AH, 37 mm, 1.5 µm), inlet and outlet plugs, and cellulose shrink bands was prepared to ensure that no air or dust escape the assembly during sampling. Prior to using the filters, they were stored in a constant humidity chamber (temperature = 25°C & relative humidity = 55%) for 24 hours to minimize the effect of humidity and temperature on the filter weight. A ¼ in male slip luer adaptor was used to connect the outlet side of the cassette to the Tygon tubing (1/4 in. internal diameter by 3/8 in outer diameter). The tube-cassette assembly was then connected to an air sampling pump (LinEair 40 LPM sampling pump, 120 VAC) consisting of a built-in flowmeter and flow control valve.

3.2.4 Dust Sampling

Six sampling points (Figure 3.1) on the elevator were established: S1(bottom plexiglass) – 23.5” from the ground, S2 (upper plexiglass) – 14.5” above S1, S3 (elevator top) – 29.5” above S2, S4 (above hopper) – 36.5” from the ground, S5 (right barrel lid), and S6 (left barrel lid). The air flow rates at these points were measured 10 times using a hot wire thermo-anemometer (Extech Instruments, Nashua, New Hampshire, U.S.A.). The measurements were averaged and were converted into standard cubic feet per hour (scfm) to match the units of the rotameter. The suction end of the Tygon tubing was placed perpendicular to the direction of air flow and the air sampling pump was adjusted to the desired flow rate to maintain near-isokinetic sampling conditions. Before and after testing, the elevator was operated for five minutes to allow self-cleaning. Grain residuals, dust, and impurities were vacuumed from the elevator in both static and running states. The ambient temperature and relative humidity were measured using a humidity sensor (Model MI70D12, Vaisala Sensor System, Helsinki, Finland).

Each replicate in the elevator consisted of 21 repeated transfers across two bins. Dust sampling for all sampling points was conducted every fourth run (1, 5, 9, 13, 17, and 21). After sampling, the air flow rates of the sampling pump were remeasured to ensure that the measurements are within 5% of the initial calibration values. The filters were stored in a constant humidity chamber for 24 hours before taking their final weight. The change in mass before and after sampling represents the mass of dust collected in the dust filter (m_d).



Back-Feed (BF) Elevator

Note: S5 and S6 are on the barrel lid connected to the discharge spout

Front-Feed (FF) Elevator

Figure 3.1 Location of sampling points in both FF and BF elevator

3.2.5 Determination of Particle Size and Particle Size Distribution

The determination of particle size (PS) and particle size distribution (PSD) of the dust were carried out using the Malvern Morphologi G3 SE (Malvern Instruments, Malvern, U.K.). A standard sample of 3 mm3 were prepared and dispersed on a glass slide using a sampling dispersion unit with pressurized air. The particles were imaged using a diascopic (bottom) light at 10x magnification, and standard operating procedures were created to randomly select 20,000 particles from the slide. After imaging, the size of the dust particles was represented by circle equivalent (CE) diameter where a 3D image of the particle was captured as a 2D image and converted to a circle of equivalent area to the 2D image (Malvern Instruments Ltd., 2015). The PSD was generated on a volume basis with focus on diameter fractions D[v,0.10], D[v,0.50], and D[v,0.90], where 0.10, 0.50, and 0.90 represents the percentage of particles with diameters less than the specified value. Volume-based distribution differs from the number-based distribution in a way that the contribution of each individual particle is proportional to its volume (Malvern Instruments Ltd., 2015).

3.2.6 Particle Shape Characterization

The particle shape descriptors which include circularity (Ci), high sensitivity circularity (HSC), convexity (Co), elongation (E), solidity (So), and aspect ratio (AR) were also determined using the same equipment and procedure discussed in the previous section. Circularity determines how close a particle shape resembles a perfect circle. It has a value ranging from 0 (narrow and elongated) to 1 (perfect circle). A more sensitive measure of Ci which is sometimes referred to as compactness is the HSC. It is calculated by getting the ratio of the particle’s projected area to the square of the perimeter of the particle. Like Ci, narrow-shaped rods have HSC close to 0 while a perfect circle has an HSC of 1. Another important shape descriptor is convexity, a factor that quantifies the surface roughness of a particle. It is obtained by getting the ratio of the convex hull perimeter and the actual particle perimeter. Least convex or smooth particles have Co close to 1 while irregular and spiky objects have Co close to 0 (Malvern Instruments Ltd., 2015).

Elongation and aspect ratio are shape descriptors related through the formula $E=1-AR$. Elongation determines how elongated a particle is while AR is used to classify the general form of particles such as fibrous, acicular, and equant (Olson, 2011). ISO 9276-6 (International Organization for Standardization [ISO], 2008) defines AR as the ratio of the Feret's minimum length to the Feret's maximum length. Both elongation and aspect ratio have values in the range 0 to 1, inclusive. Elongated particles have E values close to 1 while less elongated and more circular particles have E values close to 0. Lastly, solidity describes the overall concavity of a particle. It is calculated by dividing the area of the particle by the area of the convex hull. Like convexity, solidity is highly dependent on the convex hull. As the particle shape becomes rougher and less solid, the value of So approaches zero (Olson, 2011).

3.2.7 Data Analysis

The experimental design and data analysis were adapted from Boac et al. (2009) repeated handling study. The soybean lot was the experimental unit while the 21 transfers (with dust sampling performed every fourth run), soybean grades (G1, G3), and elevator type (FF, BF) were the class variables. All data obtained from the experiment were analyzed using Statistical Analysis Software (SAS) 9.3 (SAS Institute, Cary, NC, U.S.A.). Analysis of Variance (ANOVA) was used to compare treatment means while Tukey's Honestly Significant Difference (HSD) was used to compare significant differences ($p<0.5$) between treatment means.

3.3 Results and Discussion

3.3.1 Mass of dust collected in the filter (m_d)

The mean weight of dust collected from the dust filter for all elevator type (FF, BF) – soybean grade (G1, G3) combinations were illustrated in Figure 3.1. For all combinations, a general decreasing trend in m_d was observed when the number of repeated transfers is increased. The front-feed, soybean grade 3 (FFG3) had the most consistent trend for all sampling points where the m_d become nearly consistent and similar from the 9th run to the 21st run. Both FFG3 and BFG3 recorded the highest initial m_d at SP2. Table 3.1 shows the weight of the soybean dust collected from different sampling points of BF bucket elevator. No significant differences ($p>0.05$) in the m_d were observed for G1-S1 to S3 across all runs while the m_d of G1-S4 to S6 were significantly larger ($p<0.05$) in the first run compared to runs 9 to 21. Across sampling points, although there are differences in the amount of dust collected every run, the differences were not significant. Similar to G1 soybeans (Table 3.1), all sampling points in the first run collected the highest m_d compared to the succeeding runs. The weight of dust in the first run ranged from 10.00 mg to 39.55 mg, which were also significantly higher ($p<0.05$) than the m_d of dust obtained from G1 soybeans. However, in Run 21, the m_d from all sampling points across the two grades did not significantly vary ($p>0.05$). All grade-sampling point combinations had decreasing m_d trend as the number of runs increased except for Run 13 (G1-S5; G3-S1,S3) and Run 17 (G1-S2,S4; G3-S2).

Table 3.2 shows the m_d from different sampling points of the FF bucket elevator. For G1 soybeans, more variability in m_d was observed compared to the same soybean grade handled in the BF elevator. The highest m_d was 8.94 mg (Run 1, G1-S1) while the lowest was 1.70 mg (Run 17, G1-S6) for G1 soybeans. No significant differences were observed in the m_d of all G1-

sampling points combinations across all runs. For G3 soybeans, the m_d of S1, S2, S3, and S6 in Run 1 is significantly higher ($p<0.05$) than those in Runs 5 to 21. No significant differences ($p>0.05$) were observed for the m_d of all G3-sampling points combinations across Runs 17 and 21. Comparing the two elevators, the differences in the m_d across grades were more evident in the BF elevator than the FF elevator.

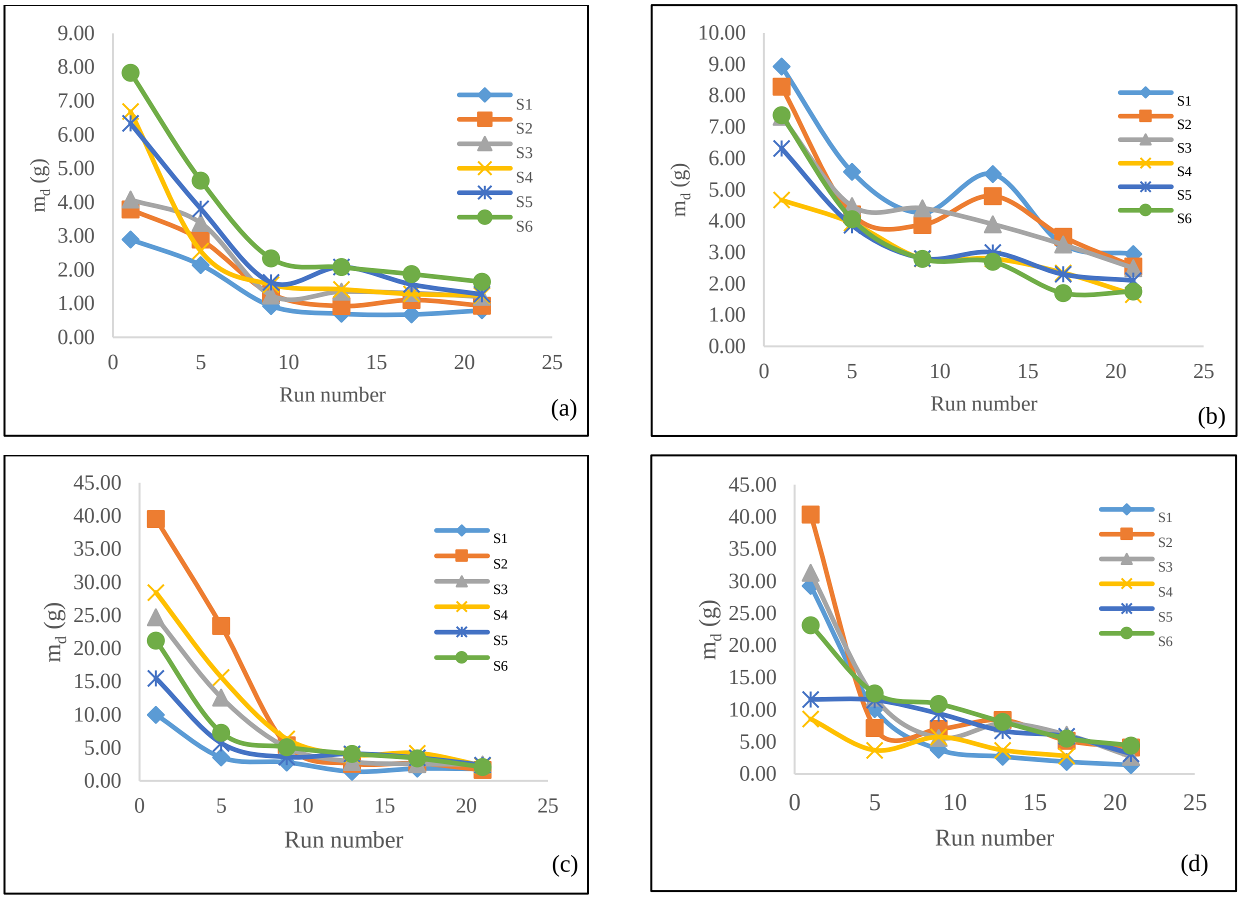


Figure 3.2 Graphs of dust weight vs run number; (a) front-feed elevator and soybean grade 1, (b) back-feed elevator and soybean grade 1, (c) front-feed elevator and soybean grade 3, (d) back-feed elevator and soybean grade 3. Abbreviations: m_d, mass of dust collected; S, sampling point.

The decreasing trend in the weight of dust collected in each sampling point contradicts the initial expectations. It was expected that dust generation will increase as the number of transfers progresses due to increasing breakage and abrasion of grains to the walls and buckets.

However, for all elevator types and soybean grades, the amount of dust collected decreased per run. It was also observed that large quantities of dust accumulated in the elevator boot and less dust were adhering on the soybeans after every transfer. This observation was different from that of Martin and Stephens' (1977) where corn dust emission had an initial build-up but remained constant despite the increase in grain breakage. Converse and Eckhoff (1989) also observed an increase in the cumulative fine material production with increasing number of transfer rotations of corn in a concrete grain elevator. The differences in the physical characteristics of soybeans and corns are the main reason why contrasting trends were observed. Fiscus, Foster, and Kaufman (1971) reported that among wheat, soybean, and corn, the latter experiences the highest breakage due to its structurally weak kernel. This makes corn kernels easy to fragmentize into random sizes during handling as compared to soybeans.

Individual weights per combination of grade and sampling point for each run in both front-feed and back-feed were summarized in Table 3.3. In comparison, only G3-S4 had significant difference ($p<0.05$) in soybean dust weight between the two elevator types during the 1st run, which remained significantly different ($p<0.05$) until the 9th run. In these runs, BF elevator obtained significantly higher soybean dust weight (run 1 – 28.45 mg, run 5 – 15.65 mg, run 9 – 6.35 mg) than FF elevator (run 1 – 8.55 mg, run 5 – 10.50 mg, run 9 – 3.70 mg). During the 5th run, only G3 soybeans resulted in significantly different ($p<0.05$) soybean dust weight at S1, S2, S4, and S5. BF elevator had significantly lower soybean dust weight at S1 (3.55 mg) and S5 (5.70 mg) and significantly higher soybean dust weight at S2 (23.40 mg) and S4 (15.65 mg) as compared to that of the FF elevator (S1 – 10.1 mg, S2 – 7.15 mg, S4 – 10.5 mg, and S5 – 11.5 mg). During the 9th run, G1 soybean dust weight was significantly different ($p<0.05$) wherein FF elevator obtained higher weight, while G3 soybean dust weight was significantly different at S4, S5, and S6. During the 13th run, more sampling points (S1, S2, and S3) had significant difference ($p<0.05$) on dust weight for G1 soybeans transferred through FF and BF elevators, while only S6 had significant difference ($p<0.05$) for grade 3 soybeans. G1-S2, G3-S3, and G3-S5 were significantly different ($p<0.05$) during the 17th run between FF and BF elevators. During the 21st run, grade 1 soybeans produced significantly higher ($p<0.05$) dust through the BF elevator at S1, S2, and S5, while no significant difference ($p>0.05$) was observed for grade 3 soybean dust weight. On the other hand, Table 3.4 shows the comparison of cumulative weight of soybean dust at different sampling points of FF and BF elevators after 21 runs. For G1 soybeans, FF elevator resulted to significantly higher ($p<0.05$) cumulative soybean dust weight (30.47 mg) at S1 as compared to that of BF elevator (8.53). Cumulative dust weight of G3 soybeans was found to be significantly higher ($p<0.05$) at S1 (49.15 mg) and S3 (65.50 mg) and significantly lower at S4 (35.00 mg) of FF elevator than that of BF elevator (S1 – 21.40 mg, S3 – 50.30 mg, and S4 – 60.90 mg).

3.3.2 Particle size and size distribution of dust

The particle size of soybean dust generated from FF and BF elevator in terms of CE diameter is listed in Tables 3.5 and 3.6. CE diameter of soybean dust did not vary ($p>0.05$) across sampling points at the same soybean grade (both 1 and 3) from 1st to 21st run for both elevator types (FF and BF). In comparing soybean dust across different runs from different grade-sampling point combinations through FF elevator, it can be observed that at S5, CE diameter of G1 soybean dust during 1st run (6.51 µm) was significantly higher ($p<0.05$) than 21st run (3.99 µm). Moreover, at S2, CE diameter of G3 soybean dust during the1st run (5.61 µm) was significantly higher ($p<0.05$) than that of 21st run. At S3 of BF elevator, G3 soybean dust had a significantly higher CE diameter during 5th run (6.41 µm) than that during 17th run (4.1

µm); at S4, significantly higher ($p<0.05$) CE diameter of G3 soybean dust was recorded during the 9th run than that of during 17th run; at S6, significantly higher ($p<0.05$) G3 soybean dust was measured during 5th run (7.18 µm) as compared to the 13th run (4.38 µm).

The diameter of soybean dust observed in this study was in the range of 3.00 µm to 8.36 µm. This is lower than the reported mass mean diameters of soybean dust from Plemons and Parnell (1981) (25.17 µm), Martin (1981) (30.00 µm), Wade, Hawk, and Watson (1979) (15.50 µm), and Parnell et al. (1986) (13.6 µm). One reason for the differences in the values is the technique used in particle size characterization. Plemons and Parnell (1981) used Coulter Counter techniques with a 400 µm aperture while Martin (1981) interpolated the results from graphical presentation of Coulter Counter results. Another reason is the source of dust. Parnell et al. (1986) obtained the soybean dust from a baghouse filter of terminal elevators while the dust used in this study was obtained by using glass fiber filters inside air sampling cassettes.

The particle size distribution of soybean dust generated from two elevator types is represented by parameters D[v,0.01], D[v,0.05], and D[v,0.09] as shown in Tables 3.7 to 3.112. For both elevators (FF and BF), no significant differences ($p<0.05$) were observed for D[v,0.01] across all sampling points and across all runs for both G1 and G3 soybean. This is also true for D[v,0.05] of soybean dust generated from FF elevator except during the 17th run of G3 soybeans, wherein significantly lower D[v,0.05] ($p<0.05$) was measured at S6 (13.15 µm) as compared to S1 (19.5 µm). In BF elevator, D[v,0.05] of G3 soybean dust generated at S2 was observed to be significantly higher ($p<0.05$) during 13th run (15.66 µm) and 21st run (16.01 µm) as compared to the 9th run (12.73 µm), while the remaining combinations of variables did not significantly vary ($p>0.05$) across sampling points and across runs for respective soybean grades. No significant difference ($p>0.05$) was observed for D[v,0.09] of soybean dust generated from both FF and BF elevators except for G3 soybean during 13th run in FF elevator, wherein significantly lower D[v,0.09] was measured at S5 (24.12 μm) and S6 (26.69 μm) as compared to S1 (50.21 μm). For G3 soybean dust collected at S2, significantly higher ($p<0.05$) D[v,0.09] was observed during the 13th run (25.38) than that during 1st run (23.12).

Although very few sampling points in the 13th run for both elevator types recorded significant differences, the overall PSD of dust across grades, runs, and sampling point did not significantly vary ($p>0.05$). This is similar to the observation of Boac et al. (2009) after repeated transfers of corn in a full-scale research elevator. However, a direct comparison cannot be made as two different grain types were studied. As of writing, there are no other publications that investigate the complete range of particle size distribution of soybean dust from repeated handling in grain elevators.

3.3.3 Particle shape analysis

High sensitivity (HS) circularity values of soybean dust collected from different sampling points of front-feed and back-feed pilot-scale grain elevators for 21 runs were listed in Tables 3.13 and 3.14, respectively. No significant differences ($p>0.05$) were observed on HS circularity of the dust particles at all sampling points for every run for both soybean grade (1 and 3) and elevator types (FF and BF). Increasing the number of runs also did not result to any significant difference ($p>0.05$) on the HS circularity of soybean dust particles collected at all sampling points.

Aspect ratio (AR) of soybean dust collected from different sampling points of front-feed and back- Moreover, only run 1 and run 5 resulted in significantly different ($p<0.05$) AR across the sampling points of FF elevator. It was also observed that the AR of G1 soybean dust collected at run 1 was significantly ($p<0.05$) less than that of G3 soybean dust collected at S1, S2, and S4 of FF elevator. On the other hand, no significant difference ($p>0.05$) was observed among the aspect ratio of soybean dust collected at different runs at the same sampling point for both G1 and G3 soybean dust through BF elevator. For G1 soybean dust, the lowest AR (0.66) was observed at S5 during the first run in BF elevator. For G3 soybean dust, the highest AR (0.70) was observed at S4 in BF elevator. Furthermore, only the first run of soybean grains through the BF elevator resulted in a significantly different ($p<0.05$) AR for both grades of soybean among different sampling points.

Tables 3.17 and 3.18 show elongation of soybean dust collected from FF and BF elevators at various grade and sampling point combinations from the 1st to 21st run. No significant differences ($p>0.05$) were observed in terms of elongation among soybean dust particles recovered from G3-sampling point combinations in the FF and BF elevator. For G1 soybean, dust collected during the first run was significantly more elongated than that during the 21st run at S1, while dust collected at S3 and S4 were significantly more elongated ($p<0.05$) as compared to the 17th run in the FF elevator. The sampling points 2, 5, and 6 of FF elevator and all sampling points of BF elevator did not result in any significant difference ($p<0.05$) in terms of elongation for G1 soybeans for all runs.

Solidity values of soybean dust collected from FF and BF elevators at various grade and sampling point combinations from the 1st to 21st runs are listed in Tables 3.19 and 3.20. In general, solidity values did not significantly differ ($p>0.05$) at different grade-sampling point combinations for all runs at FF and BF elevators. In the 5th run of G3 soybeans through FF elevator, the solidity of soybean dust collected was significantly lower ($p<0.05$) at S1 than other remaining sampling points.

Tables 3.21 and 3.22 summarize the convexity values of soybean dust particles collected from FF and BF elevators at various grade-sampling point combinations from the 1st to 21st run. No significant difference ($p<0.05$) was observed for all grade-sampling point combinations from FF and BF elevators when the number of runs was increased to 21. However, G1 soybean dust exhibited significantly higher ($p<0.05$) convexity values than the G3 soybean dust recovered at S1, S2, and S5 only during the 5th run on the FF elevator.

In summary, the measured values of HS circularity, AR, elongation, solidity, and convexity ranged from 0.70 to 0.84, 0.65 to 0.73, 0.27 to 0.35, 0.92 to 0.98, and 0.95 to 0.99, respectively. Solidity and convexity are both very high which mean that the particles have very smooth edges, and smoother and rounder surfaces. Moreover, the particles are more circular and less elongated as determined by the low value of elongation and high value of high sensitivity circularity.

3.3.4 Particulate matter (PM) percentages and comparisons

The percentages of $PM_{2.5}$ generated after several FF and BF elevator runs at different sampling points for G1 and G3 soybeans were listed in Tables 3.23 and 3.24. The percentage of $PM_{2.5}$ did not significantly differ ($p>0.05$) among soybean dust generated from different grade-sampling point combinations transferred through the FF elevator up to 21 runs. The percentage range of $PM_{2.5}$ for all of these runs at varying sampling points through the FF elevator are: run 1 (18.76-46.31%), run 5 (22.17-41.61%), run 9 (25.57-37.27%), run 13 (23.08-34.32%), run 17 (28.21-38.00%), and run 21 (27.50-37.86%). Meanwhile, for the BF elevator, all grade-sampling point combinations resulted in a non-significantly different ($p>0.05$) percentage of $PM_{2.5}$ except that of G1-S5, wherein the 13th run at this combination resulted in a significantly lower ($p<0.05$) $PM_{2.5}$ percentage, than that of the 21st run. The percentage range of $PM_{2.5}$ for all runs at varying sampling points through the BF elevator are: run 1 (26.99-51.89%), run 5 (31.67-53.71%), run 9 (22.19-51.72%), run 13 (20.41-53.13%), run 17 (27.70-43.03%), and run 21 (37.61-50.27%).

The percentages of PM_4 generated after several FF and BF elevator runs at different sampling points for G1 and G3 soybeans were listed in Tables 3.25 and 3.26. For all combinations of grade and sampling points at the FF elevator, $\%PM_4$ did not significantly vary ($p<0.05$) at increasing number of runs. This is also true for BF elevator except at G1-S2 wherein the 9th run resulted in a significantly lower ($p<0.05$) PM_4 percentage (45.41%) as compared to the 21st run (66.99%). The percentage range of PM_4 for all runs at varying sampling points through the FF elevator are: run 1 (34.27-63.76%), run 5 (39.26-59.25%), run 9 (42.96-54.75%), run 13 (40.34-53.27%), run 17 (46.98-57.73%), and run 21 (46.31-57.52%), whereas through the BF elevator are: run 1 (41.93-69.05%), run 5 (47.75-70.13%), run 9 (38.23-67.40%), run 13 (33.41-69.79%), run 17 (43.61-61.15%), and run 21 (56.11-66.99%).

The percentages of PM_{10} generated after several FF and BF elevator runs at different sampling points for G1 and G3 soybeans were listed in Tables 3.27 and 3.28. No significant difference ($p>0.05$) was observed when comparing PM_{10} percentages of soybean dust across sampling points during each run generated from both G1 and G3 soybeans through the FF and BF elevators. Only combinations G1-S2, G1-S3, G3-S3, and G3-S4 had certain runs that resulted in significant differences ($p<0.05$), while the remaining combinations did not significantly differ ($p>0.05$) during the 1st run up to the 21st run in the FF elevator. Specifically, a significantly higher ($p<0.05$) PM_{10} percentage (88.39%) during 21st run was observed for G1 soybean dust generated as compared to its 1st run both at S2 and S3 of FF elevator. Moreover, G3 soybeans generated a significantly higher ($p<0.05$) PM_{10} percentage of dust at S3 during the 21st run (92.52%) as compared to the 9th run. Also, at S4, a significantly higher ($p<0.05$) PM_{10} percentage of dust was generated during the 1st run (92.94%) as compared to the 9th run through FF elevator. In comparison, the BF elevator resulted to no significant difference ($p>0.05$) of PM_{10} percentage of soybean dust for all grade-sampling point combinations except for G1-S4, wherein a significantly lower PM_{10} percentage (80.70%) was observed during the 9th run. The percentage range of PM_{10} for all runs at varying sampling points through the FF elevator are: run 1 (78.56-92.94%), run 5 (82.49-88.84%), run 9 (81.66-88.74%), run 13 (81.38-92.93%), run 17 (86.64-91.20%), and run 21 (86.59-92.52%), whereas through the BF elevator are: run 1 (78.52-91.17%), run 5 (84.83-95.05%), run 9 (80.70-93.63%), run 13 (74.79-93.15%), run 17 (86.71-90.86%), and run 21 (87.72-92.78%).

3.4 Summary and Conclusion

Two-pilot scale bucket elevator legs were used to determine the effect of repeated handling on the quantity, particle size, size distribution, and shape characteristics (HS circularity, convexity, elongation, solidity, and aspect ratio) of soybean dust. Dust collections were carried out using glass fiber filters in an air-sampling cassette assembly. The filters were conditioned in a constant humidity chamber before and after sampling to minimize the effect of relative humidity on the filter mass. Both front-feed and back-feed elevators showed significant differences ($p<0.05$) in the weight of collected dust across grades in the first runs. The large amount of dust generated by Grade 3 soybeans was attributed to the grains' higher percentage of damaged kernels and foreign materials as compared to Grade 1 soybeans. It was also observed that the weight of the collected dust across all sampling points decreased when the number of runs was increased from 1 to 21. This observation was contrary to previous studies where an increasing amount of dust was observed for increasing number of repeated transfers. Soybeans are less dusty compared to corn wherein the majority of repeated handling studies were made. The hull of soybean is hard and water-resistant, and the overall grain structure is stronger than corn, wheat, and rice. This is one of the reasons why dust particles adhering on the hulls were easily removed after the first few transfers, which made the grains cleaner after the last run.

Another significant finding in the study is the elevator location where the highest amount of dust was collected. For both elevator types, the highest dust generation was observed in sampling points 1 (S1, lower plexiglass) and 2 (S2, upper plexiglass). S1 is situated near the elevator boot where the highest level of grain activity (incoming grain inflow from the hopper and bucket scooping) was observed. S2, on the other hand, was situated 15 in. above S1. Successive scooping of grains by the buckets shakes and agitates the grains which accelerate dust generation. This information is critical in dust explosion studies as these areas have the highest explosion potential due to high dust emission activity. As there is no published data for shape characteristics of soybean dust, the following parameters were measured and obtained – high sensitivity circularity (0.70 to 0.84), aspect ratio (0.65 to 0.73), elongation (0.27 to 0.25), solidity (0.92 to 0.98), and convexity (0.95 to 0.99). These new sets of data can provide important information for future mechanistic simulation and discrete element modeling of dust detachment from grains, dust suspension and generation, and dust explosion studies.

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3.6 Tables

Table 3.1 Weight of soybean dust collected from different sampling points of the back-feed pilot-scale bucket elevator.

Grade (G) - Sampling Point (S)	Weight (mg)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	$2.90 \pm 0.40^{a, E}$	$2.14 \pm 1.5^{a, D}$	$1.30 \pm 0.4^{a, D}$	$0.74 \pm 0.13^{a, C}$	$0.71 \pm 0.13^{a, C}$	$0.75 \pm 0.04^{a, A}$
G1-S2	$3.79 \pm 0.74^{a, E}$	$2.89 \pm 1.87^{a, D}$	$1.90 \pm 0.71^{a, D}$	$0.93 \pm 0.64^{a, BC}$	$1.10 \pm 0.37^{a, BC}$	$0.93 \pm 0.05^{a, A}$
G1-S3	$4.08 \pm 1.07^{a, E}$	$3.39 \pm 2.93^{a, D}$	$2.46 \pm 1.94^{a, CD}$	$1.19 \pm 0.3^{a, ABC}$	$1.12 \pm 0.3^{a, BC}$	$1.10 \pm 0.27^{a, A}$
G1-S4	$6.68 \pm 1.15^{a, DE}$	$2.55 \pm 1.05^{b, D}$	$1.63 \pm 0.17^{b, D}$	$1.31 \pm 0.08^{b, ABC}$	$1.17 \pm 0.28^{b, BC}$	$1.24 \pm 0.14^{b, A}$
G1-S5	$6.33 \pm 0.10^{a, DE}$	$3.80 \pm 1.59^{ab, D}$	$1.63 \pm 0.07^{bc, D}$	$2.11 \pm 0.21^{bc, ABC}$	$1.57 \pm 0.47^{bc, BC}$	$0.91 \pm 0.02^{c, A}$
G1-S6	$7.84 \pm 1.45^{a, DE}$	$4.64 \pm 2.33^{ab, CD}$	$2.57 \pm 0.35^{b, CD}$	$2.15 \pm 0.29^{b, ABC}$	$1.80 \pm 0.37^{b, ABC}$	$1.64 \pm 0.4^{b, A}$
G3-S1	$10.00 \pm 1.13^{a, DE}$	$3.55 \pm 0.49^{b, D}$	$2.80 \pm 0.28^{b, BCD}$	$1.40 \pm 0.57^{b, ABC}$	$1.85 \pm 1.2^{b, ABC}$	$1.80 \pm 0.85^{b, A}$
G3-S2	$39.55 \pm 1.06^{a, A}$	$23.40 \pm 1.84^{b, A}$	$5.40 \pm 0.28^{c, AB}$	$2.60 \pm 1.84^{c, ABC}$	$2.65 \pm 1.48^{c, ABC}$	$1.65 \pm 0.78^{c, A}$
G3-S3	$24.70 \pm 2.55^{a, BC}$	$12.60 \pm 3.39^{b, BC}$	$5.05 \pm 0.21^{c, ABC}$	$2.90 \pm 0.42^{c, ABC}$	$2.55 \pm 0.07^{c, ABC}$	$2.50 \pm 0.00^{c, A}$
G3-S4	$28.45 \pm 2.33^{a, B}$	$15.65 \pm 0.78^{b, AB}$	$6.35 \pm 0.49^{c, A}$	$3.95 \pm 0.92^{c, AB}$	$4.20 \pm 0.57^{c, A}$	$2.30 \pm 0.71^{c, A}$
G3-S5	$15.50 \pm 4.24^{a, CD}$	$5.70 \pm 0.57^{b, CD}$	$3.60 \pm 0.14^{b, BCD}$	$4.10 \pm 0.42^{b, A}$	$3.50 \pm 0.42^{b, AB}$	$2.40 \pm 0.71^{b, A}$
G3-S6	$21.20 \pm 7.21^{a, BC}$	$7.30 \pm 3.25^{b, D}$	$5.10 \pm 0.71^{b, ABC}$	$4.10 \pm 1.27^{b, A}$	$3.40 \pm 0.28^{b, AB}$	$2.10 \pm 0.99^{b, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.2 Weight of soybean dust collected from different sampling points of the front-feed pilot-scale bucket elevator.

Grade (GR) - Sampling Point (SP)	Weight (mg)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	$8.94 \pm 2.33^{a, DE}$	$5.57 \pm 1.99^{a, C}$	$4.26 \pm 1.47^{a, C}$	$5.5 \pm 0.99^{a, ABC}$	$3.25 \pm 0.92^{a, A}$	$2.95 \pm 0.07^{a, A}$
G1-S2	$8.29 \pm 2.5^{a, DE}$	$4.22 \pm 1.1^{ab, C}$	$3.88 \pm 1.55^{ab, C}$	$4.8 \pm 0.71^{ab, ABC}$	$3.5 \pm 0.14^{ab, A}$	$2.55 \pm 0.49^{b, A}$
G1-S3	$7.33 \pm 1.23^{a, DE}$	$4.48 \pm 0.17^{ab, C}$	$4.41 \pm 0.58^{ab, C}$	$3.9 \pm 0.42^{b, BC}$	$3.25 \pm 1.06^{b, A}$	$2.5 \pm 0.57^{b, A}$
G1-S4	$4.67 \pm 2.57^{a, E}$	$3.94 \pm 2.26^{a, C}$	$2.80 \pm 1.13^{a, C}$	$2.8 \pm 1.13^{a, BC}$	$2.35 \pm 0.64^{a, A}$	$1.65 \pm 0.21^{a, A}$
G1-S5	$6.32 \pm 1.8^{a, DE}$	$3.86 \pm 0.04^{ab, C}$	$2.81 \pm 0.37^{b, C}$	$3.00 \pm 0.71^{b, BC}$	$2.3 \pm 0.42^{b, A}$	$2.1 \pm 0.00^{b, A}$
G1-S6	$7.38 \pm 0.18^{a, DE}$	$4.07 \pm 0.45^{b, C}$	$2.79 \pm 0.35^{c, C}$	$2.7 \pm 0.28^{c, C}$	$1.7 \pm 0.28^{c, A}$	$1.75 \pm 0.07^{c, A}$
G3-S1	$29.25 \pm 0.35^{a, BC}$	$10.1 \pm 0.99^{b, AB}$	$3.8 \pm 1.13^{c, C}$	$2.7 \pm 0.57^{c, C}$	$1.9 \pm 1.84^{c, A}$	$1.4 \pm 0.85^{c, A}$
G3-S2	$40.35 \pm 0.35^{a, A}$	$7.15 \pm 0.49^{b, BC}$	$7 \pm 1.41^{b, ABC}$	$8.4 \pm 1.27^{b, A}$	$5.2 \pm 2.26^{b, A}$	$4.15 \pm 0.49^{b, A}$
G3-S3	$31.30 \pm 1.13^{a, B}$	$11.9 \pm 1.13^{b, A}$	$5.65 \pm 1.63^{c, BC}$	$7.85 \pm 1.91^{bc, A}$	$6.1 \pm 0.28^{c, A}$	$2.7 \pm 1.13^{c, A}$
G3-S4	$8.55 \pm 0.78^{a, DE}$	$10.5 \pm 0.85^{a, AB}$	$3.7 \pm 0.71^{bc, C}$	$5.75 \pm 0.35^{b, ABC}$	$3.7 \pm 0.28^{bc, A}$	$2.8 \pm 0.57^{c, A}$
G3-S5	$11.6 \pm 1.7^{a, D}$	$11.5 \pm 0.42^{a, AB}$	$9.4 \pm 0.14^{ab, AB}$	$6.7 \pm 1.56^{abc, AB}$	$5.85 \pm 0.64^{bc, A}$	$3.15 \pm 2.05^{c, A}$
G3-S6	$23.15 \pm 1.48^{a, B}$	$12.55 \pm 0.78^{b, A}$	$10.9 \pm 1.13^{b, A}$	$8.1 \pm 0.14^{bc, A}$	$5.55 \pm 1.91^{c, A}$	$4.45 \pm 1.63^{c, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.3 Comparison of weight of soybean dust collected from different sampling points of the front-feed and back-feed bucket elevator.

Grade (G) - Sampling Point (S)	Weight (mg)					
	Run 1		Run 5		Run 9	
	FF	BF	FF	BF	FF	BF
G1 - S1	8.94 ± 2.33^{A}	2.9 ± 0.4^{A}	5.57 ± 1.99^{A}	2.14 ± 1.5^{A}	4.26 ± 1.47^{A}	1.3 ± 0.4^{A}
G1 - S2	8.29 ± 2.5^{A}	3.79 ± 0.74^{A}	4.22 ± 1.1^{A}	2.89 ± 1.87^{A}	3.88 ± 1.55^{A}	1.9 ± 0.71^{A}
G1 - S3	7.33 ± 1.23^{A}	4.08 ± 1.07^{A}	4.48 ± 0.17^{A}	3.39 ± 2.93^{A}	4.41 ± 0.58^{A}	2.46 ± 1.94^{A}
G1 - S4	4.67 ± 2.57^{A}	6.68 ± 1.15^{A}	3.94 ± 2.26^{A}	2.55 ± 1.05^{A}	2.8 ± 1.13^{A}	1.63 ± 0.17^{A}
G1 - S5	6.32 ± 1.8^{A}	6.33 ± 0.1^{A}	3.86 ± 0.04^{A}	3.8 ± 1.59^{A}	2.81 ± 0.37^{A}	1.63 ± 0.07^{B}
G1-S6	7.38 ± 0.18^{A}	7.84 ± 1.45^{A}	4.07 ± 0.45^{A}	4.64 ± 2.33^{A}	2.79 ± 0.35^{A}	2.57 ± 0.35^{A}
G3-S1	29.25 ± 0.35^{A}	10 ± 1.13^{B}	10.1 ± 0.99^{A}	3.55 ± 0.49^{B}	3.8 ± 1.13^{A}	2.8 ± 0.28^{A}
G3-S2	40.35 ± 0.35^{A}	39.55 ± 1.06^{A}	7.15 ± 0.49^{B}	23.4 ± 1.84^{A}	7 ± 1.41^{A}	5.4 ± 0.28^{A}
G3-S3	31.3 ± 1.13^{A}	24.7 ± 2.55^{A}	11.9 ± 1.13^{A}	12.6 ± 3.39^{A}	5.65 ± 1.63^{A}	5.05 ± 0.21^{A}
G3-S4	8.55 ± 0.78^{B}	28.45 ± 2.33^{A}	10.5 ± 0.85^{B}	15.65 ± 0.78^{A}	3.7 ± 0.71^{B}	6.35 ± 0.49^{A}
G3-S5	11.6 ± 1.7^{A}	15.5 ± 4.24^{A}	11.5 ± 0.42^{A}	5.7 ± 0.57^{B}	9.4 ± 0.14^{A}	3.6 ± 0.14^{B}
G3-S6	23.15 ± 1.48^{A}	21.2 ± 7.21^{A}	12.55 ± 0.78^{A}	7.3 ± 3.25^{A}	10.9 ± 1.13^{A}	5.1 ± 0.71^{B}

Grade (G) - Sampling Point (S)	Run 13		Run 17		Run 21	
	FF	BF	FF	BF	FF	BF
G1 - S1	5.5 ± 0.99^{A}	0.74 ± 0.13^{B}	3.25 ± 0.92^{A}	0.71 ± 0.13^{A}	2.95 ± 0.07^{A}	0.75 ± 0.04^{B}
G1 - S2	4.8 ± 0.71^{A}	0.93 ± 0.64^{B}	3.5 ± 0.14^{A}	1.1 ± 0.37^{B}	2.55 ± 0.49^{A}	0.93 ± 0.05^{B}
G1 - S3	3.9 ± 0.42^{A}	1.19 ± 0.3^{B}	3.25 ± 1.06^{A}	1.12 ± 0.3^{A}	2.5 ± 0.57^{A}	1.1 ± 0.27^{A}
G1 - S4	2.8 ± 1.13^{A}	1.31 ± 0.08^{A}	2.35 ± 0.64^{A}	1.17 ± 0.28^{A}	1.65 ± 0.21^{A}	1.24 ± 0.14^{A}
G1 - S5	3 ± 0.71^{A}	2.11 ± 0.21^{A}	2.3 ± 0.42^{A}	1.57 ± 0.47^{A}	2.1 ± 0^{A}	0.91 ± 0.02^{B}
G1-S6	2.7 ± 0.28^{A}	2.15 ± 0.29^{A}	1.7 ± 0.28^{A}	1.8 ± 0.37^{A}	1.75 ± 0.07^{A}	1.64 ± 0.4^{A}
G3-S1	2.7 ± 0.57^{A}	1.4 ± 0.57^{A}	1.9 ± 1.84^{A}	1.85 ± 1.2^{A}	1.4 ± 0.85^{A}	1.8 ± 0.85^{A}
G3-S2	8.4 ± 1.27^{A}	2.6 ± 1.84^{A}	5.2 ± 2.26^{A}	2.65 ± 1.48^{A}	4.15 ± 0.49^{A}	1.65 ± 0.78^{A}
G3-S3	7.85 ± 1.91^{A}	2.9 ± 0.42^{A}	6.1 ± 0.28^{A}	2.55 ± 0.07^{B}	2.7 ± 1.13^{A}	2.5 ± 0^{A}
G3-S4	5.75 ± 0.35^{A}	3.95 ± 0.92^{A}	3.7 ± 0.28^{A}	4.2 ± 0.57^{A}	2.8 ± 0.57^{A}	2.3 ± 0.71^{A}
G3-S5	6.7 ± 1.56^{A}	4.1 ± 0.42^{A}	5.85 ± 0.64^{A}	3.5 ± 0.42^{B}	3.15 ± 2.05^{A}	2.4 ± 0.71^{A}
G3-S6	8.1 ± 0.14^{A}	4.1 ± 1.27^{B}	5.55 ± 1.91^{A}	3.4 ± 0.28^{A}	4.45 ± 1.63^{A}	2.1 ± 0.99^{A}

Note: The same uppercase superscript indicates no significant difference across the two elevator types along the same row ($p < 0.05$) per run.

Table 3.4 Comparison of cumulative weight of soybean dust collected from different sampling points of the front-feed and back-feed bucket elevator after 21 runs.

Grade (G) - Sampling Point (S)	Cumulative Weight (mg)	
	Run 1 to 21	
	FF	BF
G1 - S1	30.47 ± 5.79^{A}	8.53 ± 2.60^{B}
G1 - S2	27.23 ± 3.80^{A}	11.55 ± 4.38^{A}
G1 - S3	25.87 ± 3.69^{A}	13.32 ± 6.82^{A}
G1 - S4	18.21 ± 7.52^{A}	14.58 ± 2.52^{A}
G1 - S5	20.4 ± 3.33^{A}	16.35 ±1.85^{A}
G1-S6	20.39 ± 1.11^{A}	20.62 ±5.19^{A}
G3-S1	49.15 ± 3.04^{A}	21.4 ± 0.71^{B}
G3-S2	72.25 ± 3.61^{A}	75.25 ± 5.16^{A}
G3-S3	65.5 ± 3.39^{A}	50.3 ± 0.28^{B}
G3-S4	35 ± 0.71^{B}	60.9 ± 1.27^{A}
G3-S5	48.2 ± 3.11^{A}	34.8 ± 5.37^{A}
G3-S6	64.7 ± 5.52^{A}	43.2 ± 12.30^{A}

Note: The same uppercase superscript indicates no significant difference along the same row ($p < 0.05$).

Table 3.5 CE Diameter of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	CE Diameter (µm)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	6.28 ± 0.81$^{a, A}$	4.84 ± 0.08$^{a, A}$	5.46 ± 0.77$^{a, A}$	4.4 ± 0.2$^{a, A}$	4.37 ± 0$^{a, A}$	4.41 ± 0.29$^{a, A}$
G1-S2	6.71 ± 0.93$^{a, A}$	5.15 ± 1.3$^{a, A}$	4.84 ± 0.09$^{a, A}$	5.16 ± 0.2$^{a, A}$	4.26 ± 0.3$^{a, A}$	4.1 ± 0.75$^{a, A}$
G1-S3	5.92 ± 0.01$^{a, A}$	5.68 ± 0.44$^{a, A}$	4.95 ± 0.69$^{a, A}$	4.64 ± 0.6$^{a, A}$	3.97 ± 0.37$^{a, A}$	4.05 ± 0.62$^{a, A}$
G1-S4	5.81 ± 0.25$^{a, A}$	4.95 ± 0.86$^{a, A}$	5.4 ± 0.77$^{a, A}$	4.45 ± 0.54$^{a, A}$	4.25 ± 0.05$^{a, A}$	4.23 ± 0.38$^{a, A}$
G1-S5	6.51 ± 0.59$^{a, A}$	5.22 ± 0.66$^{ab, A}$	5.61 ± 0.43$^{ab, A}$	4.46 ± 0.58$^{ab, A}$	4.26 ± 0.33$^{ab, A}$	3.99 ± 0.89$^{b, A}$
G1-S6	5.01 ± 0.37$^{a, A}$	5.11 ± 0.86$^{a, A}$	5.97 ± 0.3$^{a, A}$	4.32 ± 0.33$^{a, A}$	4.2 ± 0.36$^{a, A}$	4.4 ± 0.83$^{a, A}$
G3-S1	5.73 ± 0.74$^{a, A}$	6.07 ± 0.06$^{a, A}$	4.93 ± 0.37$^{a, A}$	4.57 ± 0.37$^{a, A}$	6.75 ± 2.28$^{a, A}$	4.57 ± 1.8$^{a, A}$
G3-S2	5.61 ± 0.21$^{a, A}$	5.84 ± 0.05$^{a, A}$	5.11 ± 0.37$^{ab, A}$	4.78 ± 0.54$^{ab, A}$	4.73 ± 0.4$^{ab, A}$	4.1 ± 0.33$^{b, A}$
G3-S3	5.89 ± 0.72$^{a, A}$	5.52 ± 0.62$^{a, A}$	5.1 ± 0.14$^{a, A}$	5.42 ± 0.41$^{a, A}$	4.99 ± 0.55$^{a, A}$	4.89 ± 1.42$^{a, A}$
G3-S4	5.48 ± 0.24$^{a, A}$	4.83 ± 0.14$^{a, A}$	4.87 ± 1.27$^{a, A}$	5.26 ± 0.01$^{a, A}$	4.25 ± 1.82$^{a, A}$	4.23 ± 1.1$^{a, A}$
G3-S5	5.46 ± 0.58$^{a, A}$	5.54 ± 0.08$^{a, A}$	5.24 ± 0.17$^{a, A}$	4.99 ± 1.02$^{a, A}$	3.96 ± 1.36$^{a, A}$	4.86 ± 0.42$^{a, A}$
G3-S6	5.5 ± 0.61$^{a, A}$	5.14 ± 0.85$^{a, A}$	5.28 ± 0.22$^{a, A}$	4.71 ± 0.19$^{a, A}$	4.04 ± 1.12$^{a, A}$	4.95 ± 0.42$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.6 CE Diameter of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	CE Diameter (µm)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	6.73 ± 0.27$^{a, A}$	5.62 ± 0.34$^{a, AB}$	5 ± 0.13$^{a, A}$	5.57 ± 1.65$^{a, A}$	4.64 ± 0.37$^{a, A}$	4.7 ± 0.42$^{a, A}$
G1-S2	5.52 ± 0.04$^{a, A}$	4.76 ± 0.79$^{a, B}$	5.12 ± 0.16$^{a, A}$	5.34 ± 0.25$^{a, A}$	4.63 ± 0.52$^{a, A}$	4.61 ± 0.72$^{a, A}$
G1-S3	5.73 ± 0.19$^{a, A}$	4.96 ± 0.11$^{a, B}$	5.21 ± 0.97$^{a, A}$	5.18 ± 0.77$^{a, A}$	4.93 ± 1.36$^{a, A}$	4.63 ± 0.82$^{a, A}$
G1-S4	6.25 ± 0.22$^{a, A}$	5.09 ± 0.28$^{a, B}$	4.78 ± 0.65$^{a, A}$	5.35 ± 1.27$^{a, A}$	4.74 ± 0.7$^{a, A}$	4.51 ± 0.39$^{a, A}$
G1-S5	6.5 ± 0.42$^{a, A}$	5.74 ± 0.19$^{a, AB}$	5.15 ± 0.33$^{a, A}$	5.48 ± 1.44$^{a, A}$	4.59 ± 0.46$^{a, A}$	4.57 ± 0.82$^{a, A}$
G1-S6	6.16 ± 0.21$^{a, A}$	5.72 ± 0.13$^{a, AB}$	4.7 ± 0.71$^{a, A}$	5.24 ± 1.3$^{a, A}$	4.19 ± 0$^{a, A}$	4.55 ± 0.21$^{a, A}$
G3-S1	5.5 ± 0.81$^{a, A}$	5.52 ± 0.25$^{a, AB}$	5.37 ± 0.36$^{a, A}$	4.55 ± 1.03$^{a, A}$	4.02 ± 0.74$^{a, A}$	4.2 ± 0.42$^{a, A}$
G3-S2	5.4 ± 0.69$^{a, A}$	5.4 ± 0.72$^{a, AB}$	5.29 ± 1.34$^{a, A}$	5.29 ± 0.68$^{a, A}$	4.03 ± 0.5$^{a, A}$	4.77 ± 0.68$^{a, A}$
G3-S3	5.46 ± 0.23$^{ab, A}$	6.41 ± 0.19$^{a, AB}$	5.06 ± 0.45$^{ab, A}$	5.17 ± 0.34$^{ab, A}$	4.1 ± 0.97$^{b, A}$	5.11 ± 0.33$^{ab, A}$
G3-S4	5.32 ± 0.51$^{ab, A}$	5.44 ± 0.4$^{ab, AB}$	5.98 ± 0.08$^{a, A}$	4.78 ± 0.07$^{ab, A}$	4.53 ± 0.19$^{b, A}$	4.82 ± 0.37$^{ab, A}$
G3-S5	5.24 ± 0.16$^{a, A}$	5.72 ± 0.3$^{a, AB}$	5.38 ± 0.57$^{a, A}$	5.12 ± 1.09$^{a, A}$	3.9 ± 0.16$^{a, A}$	4.95 ± 0.6$^{a, A}$
G3-S6	5.48 ± 0.6$^{ab, A}$	7.18 ± 1.06$^{a, A}$	5.02 ± 0.79$^{ab, A}$	4.38 ± 0.57$^{b, A}$	4.6 ± 0.08$^{ab, A}$	4.57 ± 0.48$^{ab, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.7 D[v,0.1] of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	D[v,0.1] (μm)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	8.47 ± 1.13 $^{a, A}$	7.38 ± 1.16 $^{a, A}$	7.45 ± 1.72 $^{a, A}$	7.52 ± 0.24 $^{a, A}$	7.44 ± 0.63 $^{a, A}$	8.05 ± 0.08 $^{a, A}$
G1-S2	8.22 ± 1.05 $^{a, A}$	7.44 ± 1.46 $^{a, A}$	6.76 ± 0.4 $^{a, A}$	7.53 ± 0.01 $^{a, A}$	7.7 ± 0.09 $^{a, A}$	7.29 ± 0.26 $^{a, A}$
G1-S3	8.2 ± 0.27 $^{a, A}$	8.04 ± 0.58 $^{a, A}$	7.13 ± 0.9 $^{a, A}$	7.25 ± 0.13 $^{a, A}$	7.22 ± 0.77 $^{a, A}$	6.84 ± 0.55 $^{a, A}$
G1-S4	7.7 ± 0.48 $^{a, A}$	7.33 ± 1.54 $^{a, A}$	7.74 ± 1.55 $^{a, A}$	8.02 ± 0.55 $^{a, A}$	7.56 ± 0.4 $^{a, A}$	7.46 ± 0.13 $^{a, A}$
G1-S5	8.1 ± 0.78 $^{a, A}$	7.69 ± 0.84 $^{a, A}$	7.67 ± 0.38 $^{a, A}$	7.38 ± 0.13 $^{a, A}$	7.5 ± 0.78 $^{a, A}$	7.26 ± 0.02 $^{a, A}$
G1-S6	7.82 ± 1.16 $^{a, A}$	7.15 ± 0.9 $^{a, A}$	8.38 ± 0.48 $^{a, A}$	7.31 ± 0.33 $^{a, A}$	6.77 ± 0.35 $^{a, A}$	7.56 ± 0.24 $^{a, A}$
G3-S1	8.81 ± 0.49 $^{a, A}$	9.09 ± 1.29 $^{a, A}$	7.2 ± 0.62 $^{a, A}$	7.95 ± 0.99 $^{a, A}$	8.88 ± 3.13 $^{a, A}$	7.13 ± 0.02 $^{a, A}$
G3-S2	7.52 ± 0.57 $^{a, A}$	8.32 ± 0.77 $^{a, A}$	7.74 ± 0.06 $^{a, A}$	7.48 ± 0.11 $^{a, A}$	7.58 ± 0.72 $^{a, A}$	7.29 ± 0.01 $^{a, A}$
G3-S3	7.4 ± 0.98 $^{a, A}$	8.32 ± 0.41 $^{a, A}$	7.48 ± 0.01 $^{a, A}$	7.82 ± 0.49 $^{a, A}$	9.26 ± 2.47 $^{a, A}$	8.24 ± 0.01 $^{a, A}$
G3-S4	8.56 ± 0.72 $^{a, A}$	7.69 ± 0.21 $^{a, A}$	7.11 ± 2.34 $^{a, A}$	7.16 ± 1.05 $^{a, A}$	7.56 ± 1.94 $^{a, A}$	7.46 ± 0.01 $^{a, A}$
G3-S5	7.93 ± 1.27 $^{a, A}$	7.78 ± 0.09 $^{a, A}$	7.7 ± 0.49 $^{a, A}$	6.7 ± 0.55 $^{a, A}$	6.46 ± 0.32 $^{a, A}$	8.22 ± 0.01 $^{a, A}$
G3-S6	7.85 ± 0.85 $^{a, A}$	6.51 ± 0.9 $^{a, A}$	7.1 ± 0.32 $^{a, A}$	6.43 ± 0.64 $^{a, A}$	6.33 ± 0.3 $^{a, A}$	6.98 ± 0 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.8 D[v,0.1] of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	D[v,0.1] (μm)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	8.9 ± 0.18 $^{a, A}$	8.17 ± 0.21 $^{a, A}$	8.09 ± 0.27 $^{a, A}$	8.21 ± 0.98 $^{a, A}$	7.67 ± 0.32 $^{a, A}$	8.07 ± 0.02 $^{a, A}$
G1-S2	7.94 ± 0.28 $^{a, A}$	7.48 ± 0.39 $^{a, A}$	8.08 ± 0.07 $^{a, A}$	7.73 ± 0.29 $^{a, A}$	7.91 ± 0.3 $^{a, A}$	7.68 ± 0.56 $^{a, A}$
G1-S3	8.12 ± 0.35 $^{a, A}$	7.47 ± 0.22 $^{a, A}$	7.39 ± 1.36 $^{a, A}$	7.69 ± 0.61 $^{a, A}$	7.78 ± 0.81 $^{a, A}$	7.12 ± 0.39 $^{a, A}$
G1-S4	8.89 ± 0.76 $^{a, A}$	7.4 ± 0.85 $^{a, A}$	7.03 ± 0.71 $^{a, A}$	8.45 ± 0.61 $^{a, A}$	7.55 ± 0.02 $^{a, A}$	7.25 ± 0.31 $^{a, A}$
G1-S5	8.65 ± 0.23 $^{a, a}$	8.07 ± 0.91 $^{a, A}$	7.42 ± 0.06 $^{a, A}$	8.02 ± 0.89 $^{a, A}$	7.48 ± 0.03 $^{a, A}$	7.34 ± 0.11 $^{a, A}$
G1-S6	8.62 ± 0.02 $^{a, A}$	7.57 ± 0.43 $^{a, A}$	7.87 ± 0.28 $^{a, A}$	7.97 ± 0.93 $^{a, A}$	7.22 ± 0.63 $^{a, A}$	7.71 ± 0.22 $^{a, A}$
G3-S1	7.66 ± 0.39 $^{a, A}$	7.27 ± 0.49 $^{a, A}$	7.32 ± 0.07 $^{a, A}$	7.01 ± 0.47 $^{a, A}$	6.31 ± 0.38 $^{a, A}$	6.5 ± 1.33 $^{a, A}$
G3-S2	7.5 ± 0.44 $^{a, A}$	11.24 ± 4.88 $^{a, A}$	6.82 ± 0.72 $^{a, A}$	6.82 ± 0.24 $^{a, A}$	7.16 ± 0.05 $^{a, A}$	7.73 ± 0.27 $^{a, A}$
G3-S3	8.1 ± 0.29 $^{a, A}$	8.28 ± 0.23 $^{a, A}$	7.44 ± 1.93 $^{a, A}$	6.9 ± 0.02 $^{a, A}$	7.11 ± 0.45 $^{a, A}$	7.73 ± 0.13 $^{a, A}$
G3-S4	8.14 ± 0.67 $^{a, A}$	7.09 ± 0.33 $^{a, A}$	7.71 ± 0.22 $^{a, A}$	6.98 ± 0.33 $^{a, A}$	7.83 ± 0.94 $^{a, A}$	7.55 ± 0.7 $^{a, A}$
G3-S5	7.77 ± 0.05 $^{a, A}$	7.85 ± 1.48 $^{a, A}$	7.52 ± 0.2 $^{a, A}$	7.89 ± 0.2 $^{a, A}$	7.53 ± 0.88 $^{a, A}$	7.75 ± 0 $^{a, A}$
G3-S6	7.88 ± 0.8 $^{a, A}$	8.98 ± 1.57 $^{a, A}$	7.43 ± 0.07 $^{a, A}$	7.09 ± 0.07 $^{a, A}$	7.94 ± 0.53 $^{a, A}$	7.93 ± 0.58 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.9 D[v,0.5] of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	D[v,0.5] (μm)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	17.08 ± 2.43 $^{a, A}$	14.92 ± 1.95 $^{a, A}$	15.25 ± 3.25 $^{a, A}$	18.19 ± 0.43 $^{a, AB}$	17.29 ± 1.75 $^{a, A}$	18.24 ± 0.55 $^{a, A}$
G1-S2	15.61 ± 1.41 $^{a, A}$	15.01 ± 1.41 $^{a, A}$	14.52 ± 1.69 $^{a, A}$	16.67 ± 0.29 $^{a, ABC}$	16.4 ± 0.52 $^{a, A}$	17.03 ± 0.44 $^{a, A}$
G1-S3	15.95 ± 0.45 $^{a, A}$	16.68 ± 0.72 $^{a, A}$	14.77 ± 2.54 $^{a, A}$	15.27 ± 0.01 $^{a, ABC}$	18.04 ± 2.81 $^{a, A}$	15.67 ± 0.88 $^{a, A}$
G1-S4	15.65 ± 0.66 $^{a, A}$	15.67 ± 2.93 $^{a, A}$	17.01 ± 4.07 $^{a, A}$	17.08 ± 0.52 $^{a, ABC}$	16.88 ± 0.1 $^{a, A}$	15.87 ± 0.04 $^{a, A}$
G1-S5	15.37 ± 1.26 $^{a, A}$	15.74 ± 0.81 $^{a, A}$	16.23 ± 0.21 $^{a, A}$	15.19 ± 0.06 $^{a, ABC}$	15.53 ± 0.42 $^{a, A}$	16.37 ± 0.27 $^{a, A}$
G1-S6	17.49 ± 1.7 $^{a, A}$	16.1 ± 0.17 $^{a, A}$	17.64 ± 0.97 $^{a, A}$	15.04 ± 0.84 $^{a, ABC}$	13.99 ± 0.43 $^{a, A}$	14.88 ± 0.64 $^{a, A}$
G3-S1	17.02 ± 1.73 $^{a, A}$	18.41 ± 1.53 $^{a, A}$	16.37 ± 0.29 $^{a, A}$	19.5 ± 2.28 $^{a, A}$	17.53 ± 5.4 $^{a, A}$	16.14 ± 0.67 $^{a, A}$
G3-S2	14.61 ± 0.99 $^{a, A}$	16.69 ± 2.22 $^{a, A}$	16.84 ± 1.4 $^{a, A}$	16.07 ± 0.16 $^{a, ABC}$	16.77 ± 1.41 $^{a, A}$	17.03 ± 1.85 $^{a, A}$
G3-S3	14.48 ± 1.92 $^{a, A}$	16.95 ± 1.47 $^{a, A}$	16.14 ± 0.14 $^{a, A}$	17.5 ± 0.8 $^{a, ABC}$	18.81 ± 3.04 $^{a, A}$	17.76 ± 1.05 $^{a, A}$
G3-S4	16.38 ± 0.16 $^{a, A}$	17.49 ± 0.18 $^{a, A}$	14.74 ± 5.28 $^{a, A}$	14.51 ± 2.67 $^{a, BC}$	16.88 ± 2.81 $^{a, A}$	15.87 ± 0.54 $^{a, A}$
G3-S5	15.42 ± 2.42 $^{a, A}$	14.97 ± 0.03 $^{a, A}$	16.17 ± 1.75 $^{a, A}$	13.65 ± 0.63 $^{a, BC}$	14.53 ± 0.01 $^{a, A}$	17.58 ± 2.21 $^{a, A}$
G3-S6	14.63 ± 2.02 $^{a, A}$	12.81 ± 1.49 $^{a, A}$	14.41 ± 0.45 $^{a, A}$	13.15 ± 1.36 $^{a, C}$	14.27 ± 0.47 $^{a, A}$	15.48 ± 0.78 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.10 D[v,0.5] of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	D[v,0.5] (μm)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	17.19 ± 0.41 $^{a, A}$	16.76 ± 0.81 $^{a, A}$	16.46 ± 0.95 $^{a, A}$	17.69 ± 0.7 $^{a, A}$	16.54 ± 1.06 $^{a, A}$	17.35 ± 1.26 $^{a, A}$
G1-S2	15.83 ± 0.21 $^{a, A}$	15.74 ± 0.49 $^{a, A}$	16.45 ± 0.69 $^{a, A}$	16.25 ± 0.59 $^{a, AB}$	16.66 ± 0.38 $^{a, A}$	16.74 ± 0.41 $^{a, A}$
G1-S3	16.1 ± 0.84 $^{a, A}$	16.05 ± 0.35 $^{a, A}$	15.45 ± 2.78 $^{a, A}$	15.68 ± 0.59 $^{a, AB}$	17.73 ± 0.45 $^{a, A}$	15.56 ± 0.16 $^{a, A}$
G1-S4	18.61 ± 2.26 $^{a, A}$	15.31 ± 3.03 $^{a, A}$	14.91 ± 1.71 $^{a, A}$	17.85 ± 1.08 $^{a, A}$	16.5 ± 0.54 $^{a, A}$	15.39 ± 0.68 $^{a, A}$
G1-S5	17.35 ± 0.06 $^{a, A}$	16.77 ± 2.49 $^{a, A}$	15.61 ± 0.45 $^{a, A}$	16.27 ± 1.52 $^{a, AB}$	15.73 ± 0.29 $^{a, A}$	15.99 ± 0.54 $^{a, A}$
G1-S6	17.23 ± 0.69 $^{a, A}$	15.48 ± 0.55 $^{a, A}$	17.93 ± 0.26 $^{a, A}$	16.13 ± 1.55 $^{a, AB}$	16.05 ± 2.92 $^{a, A}$	16.4 ± 2.15 $^{a, A}$
G3-S1	14.24 ± 0.01 $^{a, A}$	14.14 ± 0.16 $^{a, A}$	14.77 ± 0.25 $^{a, A}$	14.68 ± 0.78 $^{a, AB}$	13.26 ± 0.2 $^{a, A}$	13.18 ± 2.81 $^{a, A}$
G3-S2	13.95 ± 0.08 $^{ab, A}$	14.32 ± 0.78 $^{ab, A}$	12.73 ± 1.1 $^{b, A}$	15.66 ± 0.04 $^{a, AB}$	14.6 ± 0.4 $^{ab, A}$	16.01 ± 0.86 $^{a, A}$
G3-S3	15.72 ± 1.05 $^{a, A}$	16.19 ± 0.83 $^{a, A}$	14.42 ± 2.72 $^{a, A}$	13.85 ± 0.84 $^{a, B}$	16.6 ± 2.64 $^{a, A}$	16.05 ± 1.91 $^{a, A}$
G3-S4	16.63 ± 2.23 $^{a, A}$	14.04 ± 1.84 $^{a, A}$	15.55 ± 0.14 $^{a, A}$	14.04 ± 0.01 $^{a, B}$	15.65 ± 1.49 $^{a, A}$	16.51 ± 0.62 $^{a, A}$
G3-S5	15.74 ± 1.58 $^{a, A}$	16.21 ± 3.58 $^{a, A}$	15.27 ± 1.21 $^{a, A}$	16.15 ± 0.98 $^{a, AB}$	17.31 ± 5.59 $^{a, A}$	17.12 ± 0.28 $^{a, A}$
G3-S6	14.91 ± 1.55 $^{a, A}$	16.63 ± 2.7 $^{a, A}$	14.88 ± 0.74 $^{a, A}$	15.36 ± 0.33 $^{a, AB}$	16.4 ± 0.96 $^{a, A}$	17.04 ± 1.93 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.11 D[v,0.9] of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	D[v,0.9] (µm)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	37.15 ± 10.77 $^{a, A}$	40.9 ± 18.32 $^{a, A}$	30.33 ± 3.54 $^{a, A}$	43.73 ± 1.7 $^{a, AB}$	47.69 ± 2.5 $^{a, A}$	35.24 ± 0.63 $^{a, A}$
G1-S2	27.33 ± 1.05 $^{a, A}$	28.38 ± 1.27 $^{a, A}$	28.25 ± 0.61 $^{a, A}$	32.46 ± 1.41 $^{a, AB}$	31.11 ± 2.64 $^{a, A}$	32.55 ± 2.63 $^{a, A}$
G1-S3	28.55 ± 0.18 $^{a, A}$	48.09 ± 0.98 $^{a, A}$	32.35 ± 12.17 $^{a, A}$	28.64 ± 0.93 $^{a, AB}$	40.92 ± 8.11 $^{a, A}$	28.38 ± 0.35 $^{a, A}$
G1-S4	28.01 ± 1.28 $^{a, A}$	30.51 ± 4.2 $^{a, A}$	31.85 ± 9.16 $^{a, A}$	31.63 ± 5.4 $^{a, AB}$	36.47 ± 2.38 $^{a, A}$	30.67 ± 0.51 $^{a, A}$
G1-S5	27.19 ± 3.71 $^{a, A}$	30.32 ± 3.9 $^{a, A}$	34.95 ± 10.78 $^{a, A}$	28.67 ± 0.03 $^{a, AB}$	27.59 ± 1.69 $^{a, A}$	44.6 ± 7.01 $^{a, A}$
G1-S6	37.81 ± 11.72 $^{a, A}$	30.83 ± 2.82 $^{a, A}$	35.81 ± 4.77 $^{a, A}$	27.6 ± 0.69 $^{a, B}$	24.71 ± 1.87 $^{a, A}$	26.48 ± 1.73 $^{a, A}$
G3-S1	35.06 ± 10.8 $^{a, A}$	41.6 ± 2.16 $^{a, A}$	41.89 ± 9.07 $^{a, A}$	50.21 ± 12.01 $^{a, A}$	36.36 ± 9.38 $^{a, A}$	37.19 ± 8.8 $^{a, A}$
G3-S2	25.01 ± 0.31 $^{a, A}$	35.53 ± 7.47 $^{a, A}$	40.16 ± 7.21 $^{a, A}$	34.27 ± 0.04 $^{a, AB}$	32.4 ± 0.84 $^{a, A}$	32.55 ± 12.62 $^{a, A}$
G3-S3	28.86 ± 4.66 $^{a, A}$	35.93 ± 11.94 $^{a, A}$	34.28 ± 3.91 $^{a, A}$	40.12 ± 10.26 $^{a, AB}$	38.01 ± 2.12 $^{a, A}$	37.17 ± 7.22 $^{a, A}$
G3-S4	38.89 ± 1.54 $^{a, A}$	39.2 ± 2.94 $^{a, A}$	29.73 ± 10.39 $^{a, A}$	32.35 ± 8.84 $^{a, AB}$	36.47 ± 8.88 $^{a, A}$	30.67 ± 2.75 $^{a, A}$
G3-S5	27.56 ± 7.1 $^{a, A}$	27.42 ± 0.04 $^{a, A}$	35.43 ± 6.39 $^{a, A}$	26.69 ± 3.3 $^{a, B}$	33.66 ± 6.82 $^{a, A}$	40.7 ± 13.65 $^{a, A}$
G3-S6	26.21 ± 2.52 $^{a, A}$	30.6 ± 4.82 $^{a, A}$	28.37 ± 3.59 $^{a, A}$	24.12 ± 1.5 $^{a, B}$	35.92 ± 12.01 $^{a, A}$	33.88 ± 4.7 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.12 D[v,0.9] of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	D[v,0.9] (µm)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	30.61 ± 0.97 $^{a, A}$	34.5 ± 6.72 $^{a, A}$	29.2 ± 0.98 $^{a, A}$	37.17 ± 9.28 $^{a, A}$	38.1 ± 13.57 $^{a, A}$	32.22 ± 4.27 $^{a, A}$
G1-S2	27.11 ± 1.18 $^{a, A}$	32.45 ± 1.29 $^{a, A}$	35.93 ± 13.49 $^{a, A}$	29.78 ± 3.79 $^{a, A}$	38.29 ± 10.15 $^{a, A}$	34.24 ± 2.39 $^{a, A}$
G1-S3	29.46 ± 2.8 $^{a, A}$	33.29 ± 6.17 $^{a, A}$	28.03 ± 4.31 $^{a, A}$	29.05 ± 0.58 $^{a, A}$	35.99 ± 6.96 $^{a, A}$	28.2 ± 0.25 $^{a, A}$
G1-S4	44.56 ± 10.08 $^{a, A}$	28.64 ± 6.21 $^{a, A}$	30.6 ± 3.3 $^{a, A}$	38.09 ± 9.15 $^{a, A}$	34.7 ± 2.5 $^{a, A}$	30.63 ± 0.05 $^{a, A}$
G1-S5	35.84 ± 2.23 $^{a, A}$	32 ± 5.9 $^{a, A}$	33.08 ± 6.36 $^{a, A}$	32.26 ± 5.07 $^{a, A}$	32.58 ± 7.06 $^{a, A}$	38.84 ± 8.15 $^{a, A}$
G1-S6	32.17 ± 1.99 $^{a, A}$	27.75 ± 0.95 $^{a, A}$	36.61 ± 0.3 $^{a, A}$	29.88 ± 3.24 $^{a, A}$	30.76 ± 8.57 $^{a, A}$	31.54 ± 7.16 $^{a, A}$
G3-S1	24.25 ± 0.87 $^{a, A}$	26.52 ± 2.09 $^{a, A}$	27.58 ± 0.49 $^{a, A}$	30.91 ± 5.89 $^{a, A}$	26.07 ± 5.76 $^{a, A}$	24.52 ± 4.37 $^{a, A}$
G3-S2	23.12 ± 0.69 $^{b, A}$	24.14 ± 1.98 $^{ab, A}$	25.38 ± 0.57 $^{ab, A}$	25.38 ± 3.52 $^{a, A}$	26.75 ± 0.37 $^{ab, A}$	30.34 ± 4.57 $^{ab, A}$
G3-S3	32.34 ± 8.45 $^{a, A}$	29.62 ± 3.13 $^{a, A}$	31.51 ± 13.24 $^{a, A}$	45.76 ± 30.27 $^{a, A}$	36.25 ± 8.34 $^{a, A}$	34.81 ± 13.8 $^{a, A}$
G3-S4	40.04 ± 18.2 $^{a, A}$	25.52 ± 5.01 $^{a, A}$	33.9 ± 7.93 $^{a, A}$	27.89 ± 1.35 $^{a, A}$	30.23 ± 4.33 $^{a, A}$	41.85 ± 19.09 $^{a, A}$
G3-S5	33.4 ± 7.74 $^{a, A}$	35.69 ± 12.78 $^{a, A}$	35.4 ± 15.26 $^{a, A}$	36.91 ± 12.99 $^{a, A}$	36.93 ± 18.67 $^{a, A}$	35.49 ± 3.38 $^{a, A}$
G3-S6	27.58 ± 5.11 $^{a, A}$	29.33 ± 5.13 $^{a, A}$	28.33 ± 3.43 $^{a, A}$	31.46 ± 0.2 $^{a, A}$	28.56 ± 2.1 $^{a, A}$	39.25 ± 19.81 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.13 HS Circularity of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	HS Circularity					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	0.78 ± 0.02 $^{a, A}$	0.81 ± 0.02 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.8 ± 0.01 $^{a, A}$
G1-S2	0.78 ± 0.02 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.8 ± 0.02 $^{a, A}$	0.77 ± 0.02 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.8 ± 0.03 $^{a, A}$
G1-S3	0.79 ± 0 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.8 ± 0.02 $^{a, A}$	0.82 ± 0.01 $^{a, A}$	0.81 ± 0.02 $^{a, A}$
G1-S4	0.79 ± 0.01 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.81 ± 0.02 $^{a, A}$	0.81 ± 0.02 $^{a, A}$	0.8 ± 0.02 $^{a, A}$
G1-S5	0.78 ± 0.02 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.79 ± 0 $^{a, A}$	0.8 ± 0.03 $^{a, A}$	0.8 ± 0.02 $^{a, A}$	0.81 ± 0.04 $^{a, A}$
G1-S6	0.8 ± 0 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.79 ± 0 $^{a, A}$	0.81 ± 0.01 $^{a, A}$	0.79 ± 0.03 $^{a, A}$	0.79 ± 0.04 $^{a, A}$
G3-S1	0.79 ± 0.01 $^{a, A}$	0.78 ± 0.01 $^{a, A}$	0.79 ± 0 $^{a, A}$	0.82 ± 0 $^{a, A}$	0.76 ± 0 $^{a, A}$	0.78 ± 0 $^{a, A}$
G3-S2	0.8 ± 0.01 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.81 ± 0 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.8 ± 0.01 $^{a, A}$
G3-S3	0.77 ± 0 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.79 ± 0 $^{a, A}$	0.78 ± 0.01 $^{a, A}$	0.8 ± 0.02 $^{a, A}$	0.8 ± 0.01 $^{a, A}$
G3-S4	0.8 ± 0.01 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.78 ± 0.01 $^{a, A}$	0.81 ± 0.01 $^{a, A}$	0.8 ± 0 $^{a, A}$
G3-S5	0.79 ± 0.01 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.81 ± 0 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.8 ± 0.02 $^{a, A}$
G3-S6	0.79 ± 0 $^{a, A}$	0.79 ± 0 $^{a, A}$	0.77 ± 0 $^{a, A}$	0.79 ± 0 $^{a, A}$	0.81 ± 0.01 $^{a, A}$	0.78 ± 0.02 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.14 HS Circularity of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	HS Circularity					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	0.76 ± 0.01 $^{a, A}$	0.77 ± 0.03 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.78 ± 0.03 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.8 ± 0 $^{a, A}$
G1-S2	0.79 ± 0.01 $^{a, A}$	0.81 ± 0.02 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.78 ± 0.01 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.8 ± 0 $^{a, A}$
G1-S3	0.79 ± 0.01 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.79 ± 0.02 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.79 ± 0.03 $^{a, A}$	0.8 ± 0.01 $^{a, A}$
G1-S4	0.79 ± 0 $^{a, A}$	0.81 ± 0 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.8 ± 0.01 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.8 ± 0 $^{a, A}$
G1-S5	0.76 ± 0.03 $^{a, A}$	0.78 ± 0.02 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.78 ± 0.03 $^{a, A}$	0.8 ± 0 $^{a, A}$	0.8 ± 0.01 $^{a, A}$
G1-S6	0.78 ± 0.01 $^{a, A}$	0.79 ± 0 $^{a, A}$	0.8 ± 0.02 $^{a, A}$	0.8 ± 0.02 $^{a, A}$	0.8 ± 0.02 $^{a, A}$	0.8 ± 0.01 $^{a, A}$
G3-S1	0.8 ± 0.01 $^{a, A}$	0.77 ± 0.02 $^{a, A}$	0.76 ± 0.01 $^{a, A}$	0.79 ± 0.03 $^{a, A}$	0.81 ± 0.01 $^{a, A}$	0.8 ± 0 $^{a, A}$
G3-S2	0.79 ± 0.03 $^{a, A}$	0.78 ± 0 $^{a, A}$	0.75 ± 0.07 $^{a, A}$	0.75 ± 0.03 $^{a, A}$	0.82 ± 0.01 $^{a, A}$	0.8 ± 0.01 $^{a, A}$
G3-S3	0.79 ± 0.01 $^{a, A}$	0.78 ± 0.02 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.78 ± 0.03 $^{a, A}$	0.82 ± 0 $^{a, A}$	0.79 ± 0.01 $^{a, A}$
G3-S4	0.8 ± 0.02 $^{a, A}$	0.79 ± 0.02 $^{a, A}$	0.78 ± 0.01 $^{a, A}$	0.79 ± 0.01 $^{a, A}$	0.8 ± 0.02 $^{a, A}$	0.8 ± 0 $^{a, A}$
G3-S5	0.79 ± 0.01 $^{a, A}$	0.77 ± 0.04 $^{a, A}$	0.77 ± 0.04 $^{a, A}$	0.79 ± 0.04 $^{a, A}$	0.81 ± 0.02 $^{a, A}$	0.79 ± 0.02 $^{a, A}$
G3-S6	0.79 ± 0.01 $^{a, A}$	0.74 ± 0.03 $^{a, A}$	0.79 ± 0.04 $^{a, A}$	0.81 ± 0.01 $^{a, A}$	0.79 ± 0 $^{a, A}$	0.8 ± 0.01 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.15 Aspect ratio of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	Aspect Ratio					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	0.66 ± 0.01$^{c, CD}$	0.68 ± 0.01$^{abc, AB}$	0.67 ± 0$^{bc, A}$	0.7 ± 0$^{a, A}$	0.69 ± 0$^{ab, A}$	0.7 ± 0$^{a, A}$
G1-S2	0.66 ± 0.01$^{a, D}$	0.67 ± 0.01$^{a, B}$	0.68 ± 0.01$^{a, A}$	0.67 ± 0$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.7 ± 0.01$^{a, A}$
G1-S3	0.67 ± 0$^{b, CD}$	0.67 ± 0$^{ab, B}$	0.68 ± 0$^{ab, A}$	0.69 ± 0.01$^{ab, A}$	0.71 ± 0.02$^{a, A}$	0.7 ± 0.01$^{ab, A}$
G1-S4	0.67 ± 0.01$^{b, BCD}$	0.68 ± 0.01$^{ab, AB}$	0.68 ± 0$^{ab, A}$	0.69 ± 0.01$^{ab, A}$	0.7 ± 0.01$^{b, A}$	0.69 ± 0$^{ab, A}$
G1-S5	0.66 ± 0.01$^{a, D}$	0.68 ± 0.01$^{a, AB}$	0.67 ± 0$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.7 ± 0$^{a, A}$	0.69 ± 0.02$^{a, A}$
G1-S6	0.68 ± 0$^{a, ABCD}$	0.67 ± 0$^{a, B}$	0.67 ± 0$^{a, A}$	0.7 ± 0$^{a, A}$	0.68 ± 0.01$^{a, A}$	0.69 ± 0.02$^{a, A}$
G3-S1	0.7 ± 0$^{a, AB}$	0.7 ± 0$^{a, AB}$	0.7 ± 0$^{a, A}$	0.71 ± 0.03$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.7 ± 0.02$^{a, A}$
G3-S2	0.7 ± 0$^{a, ABC}$	0.7 ± 0.01$^{a, AB}$	0.7 ± 0.01$^{a, A}$	0.7 ± 0.03$^{a, A}$	0.7 ± 0$^{a, A}$	0.7 ± 0$^{a, A}$
G3-S3	0.69 ± 0.01$^{a, ABCD}$	0.7 ± 0$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.69 ± 0$^{a, A}$	0.71 ± 0.02$^{a, A}$
G3-S4	0.71 ± 0.01$^{a, A}$	0.7 ± 0.01$^{a, AB}$	0.69 ± 0.01$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.7 ± 0$^{a, A}$	0.69 ± 0.02$^{a, A}$
G3-S5	0.71 ± 0.01$^{a, A}$	0.7 ± 0$^{a, AB}$	0.69 ± 0$^{a, A}$	0.69 ± 0$^{a, A}$	0.71 ± 0.01$^{a, A}$	0.71 ± 0.02$^{a, A}$
G3-S6	0.7 ± 0.01$^{a, A}$	0.69 ± 0.01$^{a, AB}$	0.68 ± 0.02$^{a, A}$	0.69 ± 0$^{a, A}$	0.71 ± 0.01$^{a, A}$	0.7 ± 0.01$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.16 Aspect ratio of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	Aspect Ratio					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	0.66 ± 0$^{a, BC}$	0.66 ± 0.02$^{a, A}$	0.68 ± 0$^{a, A}$	0.68 ± 0.03$^{a, A}$	0.68 ± 0.01$^{a, A}$	0.69 ± 0.01$^{a, A}$
G1-S2	0.67 ± 0$^{a, ABC}$	0.68 ± 0.01$^{a, A}$	0.68 ± 0$^{a, A}$	0.67 ± 0$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.69 ± 0.01$^{a, A}$
G1-S3	0.67 ± 0.01$^{a, ABC}$	0.67 ± 0.01$^{a, A}$	0.67 ± 0.01$^{a, A}$	0.68 ± 0.01$^{a, A}$	0.69 ± 0.03$^{a, A}$	0.68 ± 0.02$^{a, A}$
G1-S4	0.67 ± 0$^{a, ABC}$	0.68 ± 0$^{a, A}$	0.68 ± 0$^{a, A}$	0.68 ± 0.02$^{a, A}$	0.69 ± 0.02$^{a, A}$	0.68 ± 0.01$^{a, A}$
G1-S5	0.66 ± 0.02$^{a, C}$	0.67 ± 0.02$^{a, A}$	0.67 ± 0.01$^{a, A}$	0.67 ± 0.03$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.68 ± 0.02$^{a, A}$
G1-S6	0.67 ± 0$^{a, ABC}$	0.67 ± 0$^{a, A}$	0.68 ± 0.02$^{a, A}$	0.68 ± 0.02$^{a, A}$	0.69 ± 0$^{a, A}$	0.68 ± 0$^{a, A}$
G3-S1	0.69 ± 0.01$^{a, ABC}$	0.68 ± 0.01$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.7 ± 0$^{a, A}$	0.7 ± 0.02$^{a, A}$	0.7 ± 0$^{a, A}$
G3-S2	0.69 ± 0.02$^{a, ABC}$	0.68 ± 0.01$^{a, A}$	0.68 ± 0.02$^{a, A}$	0.68 ± 0$^{a, A}$	0.7 ± 0.02$^{a, A}$	0.7 ± 0.01$^{a, A}$
G3-S3	0.7 ± 0$^{a, AB}$	0.69 ± 0.01$^{a, A}$	0.7 ± 0.01$^{a, A}$	0.68 ± 0$^{a, A}$	0.7 ± 0.02$^{a, A}$	0.69 ± 0.01$^{a, A}$
G3-S4	0.7 ± 0.02$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.68 ± 0.01$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.69 ± 0$^{a, A}$	0.7 ± 0$^{a, A}$
G3-S5	0.7 ± 0.01$^{a, AB}$	0.69 ± 0.01$^{a, A}$	0.68 ± 0$^{a, A}$	0.69 ± 0.01$^{a, A}$	0.71 ± 0.01$^{a, A}$	0.69 ± 0.01$^{a, A}$
G3-S6	0.7 ± 0.01$^{a, ABC}$	0.67 ± 0.01$^{a, A}$	0.69 ± 0$^{a, A}$	0.7 ± 0.02$^{a, A}$	0.7 ± 0$^{a, A}$	0.7 ± 0.01$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.17 Elongation of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	Elongation					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	$0.34 \pm 0.01^{a, A}$	$0.32 \pm 0.01^{ab, AB}$	$0.33 \pm 0^{ab, A}$	$0.3 \pm 0^{b, A}$	$0.31 \pm 0^{ab, A}$	$0.3 \pm 0^{b, A}$
G1-S2	$0.34 \pm 0.01^{a, A}$	$0.33 \pm 0.01^{a, A}$	$0.32 \pm 0.01^{a, A}$	$0.33 \pm 0^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.3 \pm 0.01^{a, A}$
G1-S3	$0.33 \pm 0^{a, AB}$	$0.33 \pm 0^{ab, A}$	$0.32 \pm 0^{ab, A}$	$0.31 \pm 0.01^{ab, A}$	$0.29 \pm 0.02^{b, A}$	$0.3 \pm 0.01^{ab, A}$
G1-S4	$0.33 \pm 0.01^{a, ABC}$	$0.32 \pm 0.01^{ab, AB}$	$0.33 \pm 0^{ab, A}$	$0.31 \pm 0.01^{ab, A}$	$0.3 \pm 0.01^{b, A}$	$0.31 \pm 0^{ab, A}$
G1-S5	$0.34 \pm 0.01^{a, A}$	$0.32 \pm 0.01^{a, AB}$	$0.33 \pm 0^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.31 \pm 0^{a, A}$	$0.31 \pm 0.02^{a, A}$
G1-S6	$0.32 \pm 0^{a, ABCD}$	$0.33 \pm 0^{a, A}$	$0.33 \pm 0^{a, A}$	$0.3 \pm 0^{a, A}$	$0.32 \pm 0.01^{a, A}$	$0.32 \pm 0.02^{a, A}$
G3-S1	$0.3 \pm 0^{a, BCD}$	$0.3 \pm 0^{a, AB}$	$0.3 \pm 0^{a, A}$	$0.29 \pm 0.03^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.3 \pm 0.02^{a, A}$
G3-S2	$0.3 \pm 0^{a, BCD}$	$0.3 \pm 0.01^{a, AB}$	$0.31 \pm 0.01^{a, A}$	$0.3 \pm 0.03^{a, A}$	$0.3 \pm 0^{a, A}$	$0.3 \pm 0^{a, A}$
G3-S3	$0.31 \pm 0.01^{a, ABCD}$	$0.3 \pm 0^{a, B}$	$0.31 \pm 0.01^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.31 \pm 0^{a, A}$	$0.29 \pm 0.02^{a, A}$
G3-S4	$0.29 \pm 0.01^{a, D}$	$0.3 \pm 0.01^{a, AB}$	$0.31 \pm 0.01^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.3 \pm 0^{a, A}$	$0.31 \pm 0.02^{a, A}$
G3-S5	$0.29 \pm 0.01^{a, D}$	$0.3 \pm 0^{a, AB}$	$0.31 \pm 0^{a, A}$	$0.31 \pm 0^{a, A}$	$0.3 \pm 0.01^{a, A}$	$0.29 \pm 0.02^{a, A}$
G3-S6	$0.3 \pm 0.01^{a, CD}$	$0.31 \pm 0.01^{a, AB}$	$0.32 \pm 0.02^{a, A}$	$0.31 \pm 0^{a, A}$	$0.29 \pm 0.01^{a, A}$	$0.3 \pm 0.01^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.18 Elongation of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	Elongation					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	$0.34 \pm 0^{a, AB}$	$0.34 \pm 0.02^{a, A}$	$0.32 \pm 0^{a, A}$	$0.32 \pm 0.03^{a, A}$	$0.32 \pm 0.01^{a, A}$	$0.31 \pm 0.01^{a, A}$
G1-S2	$0.33 \pm 0^{a, ABC}$	$0.32 \pm 0.01^{a, A}$	$0.32 \pm 0^{a, A}$	$0.33 \pm 0^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.31 \pm 0.01^{a, A}$
G1-S3	$0.33 \pm 0.01^{a, ABC}$	$0.33 \pm 0.01^{a, A}$	$0.33 \pm 0.01^{a, A}$	$0.32 \pm 0.01^{a, A}$	$0.31 \pm 0.03^{a, A}$	$0.32 \pm 0.02^{a, A}$
G1-S4	$0.33 \pm 0^{a, ABC}$	$0.32 \pm 0^{a, A}$	$0.32 \pm 0^{a, A}$	$0.32 \pm 0.02^{a, A}$	$0.31 \pm 0.02^{a, A}$	$0.32 \pm 0.01^{a, A}$
G1-S5	$0.34 \pm 0.02^{a, A}$	$0.33 \pm 0.02^{a, A}$	$0.33 \pm 0.01^{a, A}$	$0.33 \pm 0.03^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.32 \pm 0.02^{a, A}$
G1-S6	$0.33 \pm 0^{a, ABC}$	$0.33 \pm 0^{a, A}$	$0.32 \pm 0.02^{a, A}$	$0.32 \pm 0.02^{a, A}$	$0.31 \pm 0^{a, A}$	$0.32 \pm 0^{a, A}$
G3-S1	$0.31 \pm 0.01^{a, ABC}$	$0.32 \pm 0.01^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.3 \pm 0^{a, A}$	$0.3 \pm 0.02^{a, A}$	$0.3 \pm 0^{a, A}$
G3-S2	$0.31 \pm 0.02^{a, ABC}$	$0.32 \pm 0.01^{a, A}$	$0.32 \pm 0.02^{a, A}$	$0.32 \pm 0^{a, A}$	$0.3 \pm 0.02^{a, A}$	$0.3 \pm 0.01^{a, A}$
G3-S3	$0.3 \pm 0^{a, BC}$	$0.31 \pm 0.01^{a, A}$	$0.3 \pm 0.01^{a, A}$	$0.32 \pm 0^{a, A}$	$0.3 \pm 0.02^{a, A}$	$0.31 \pm 0.01^{a, A}$
G3-S4	$0.3 \pm 0.02^{a, C}$	$0.31 \pm 0.01^{a, A}$	$0.32 \pm 0.01^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.31 \pm 0^{a, A}$	$0.3 \pm 0^{a, A}$
G3-S5	$0.3 \pm 0.01^{a, BC}$	$0.31 \pm 0.01^{a, A}$	$0.32 \pm 0^{a, A}$	$0.31 \pm 0.01^{a, A}$	$0.29 \pm 0.01^{a, A}$	$0.31 \pm 0.01^{a, A}$
G3-S6	$0.3 \pm 0.01^{a, ABC}$	$0.33 \pm 0.01^{a, A}$	$0.31 \pm 0^{a, A}$	$0.3 \pm 0.02^{a, A}$	$0.3 \pm 0^{a, A}$	$0.3 \pm 0.01^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.19 Solidity of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	Solidity					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	0.96 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$
G1-S2	0.96 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$
G1-S3	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$
G1-S4	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, AB}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$
G1-S5	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.02$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$
G1-S6	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.96 ± 0.02$^{a, A}$
G3-S1	0.96 ± 0.01$^{a, A}$	0.95 ± 0$^{a, B}$	0.96 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.95 ± 0.01$^{a, A}$	0.95 ± 0.03$^{a, A}$
G3-S2	0.96 ± 0.01$^{a, A}$	0.96 ± 0$^{a, AB}$	0.96 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.97 ± 0$^{a, A}$
G3-S3	0.95 ± 0$^{a, A}$	0.96 ± 0$^{a, AB}$	0.96 ± 0.01$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.96 ± 0.02$^{a, A}$
G3-S4	0.96 ± 0$^{a, A}$	0.96 ± 0$^{a, AB}$	0.97 ± 0$^{a, A}$	0.95 ± 0.02$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.02$^{a, A}$
G3-S5	0.95 ± 0.01$^{a, A}$	0.96 ± 0$^{a, AB}$	0.97 ± 0$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.96 ± 0$^{a, A}$
G3-S6	0.96 ± 0.01$^{a, A}$	0.96 ± 0.01$^{a, AB}$	0.95 ± 0.02$^{a, A}$	0.96 ± 0.03$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.95 ± 0.01$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.20 Solidity of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	Solidity					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	0.96 ± 0.01$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G1-S2	0.96 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G1-S3	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G1-S4	0.96 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G1-S5	0.95 ± 0.01$^{a, A}$	0.96 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G1-S6	0.96 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$
G3-S1	0.96 ± 0.01$^{a, A}$	0.95 ± 0.01$^{a, A}$	0.94 ± 0.01$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.97 ± 0$^{a, A}$	0.96 ± 0$^{a, A}$
G3-S2	0.96 ± 0$^{a, A}$	0.95 ± 0$^{a, A}$	0.94 ± 0.04$^{a, A}$	0.94 ± 0.02$^{a, A}$	0.97 ± 0$^{a, A}$	0.96 ± 0$^{a, A}$
G3-S3	0.96 ± 0$^{a, A}$	0.95 ± 0.02$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.95 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.96 ± 0$^{a, A}$
G3-S4	0.96 ± 0.01$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.95 ± 0.01$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.96 ± 0$^{a, A}$
G3-S5	0.96 ± 0.01$^{a, A}$	0.95 ± 0.02$^{a, A}$	0.95 ± 0.02$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.96 ± 0.01$^{a, A}$
G3-S6	0.96 ± 0$^{a, A}$	0.94 ± 0.02$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.96 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.21 Convexity of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	Convexity					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$
G1-S2	0.97 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$
G1-S3	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, AB}$	0.98 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$
G1-S4	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, AB}$	0.98 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$	0.98 ± 0.01$^{a, A}$	0.98 ± 0.01$^{a, A}$
G1-S5	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, AB}$	0.97 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0.01$^{a, A}$
G1-S6	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, ABC}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0.01$^{a, A}$
G3-S1	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, D}$	0.97 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.96 ± 0$^{a, A}$	0.97 ± 0.02$^{a, A}$
G3-S2	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, CD}$	0.97 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0.01$^{a, A}$
G3-S3	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, BCD}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$
G3-S4	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, BDC}$	0.98 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$
G3-S5	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, CD}$	0.98 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0.02$^{a, A}$	0.97 ± 0.01$^{a, A}$
G3-S6	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, BCD}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.02$^{a, A}$	0.97 ± 0$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.22 Convexity of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	Convexity					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$
G1-S2	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$
G1-S3	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$
G1-S4	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$
G1-S5	0.97 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$
G1-S6	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$
G3-S1	0.97 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G3-S2	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.96 ± 0.02$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G3-S3	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G3-S4	0.97 ± 0$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$	0.98 ± 0.01$^{a, A}$	0.97 ± 0$^{a, A}$
G3-S5	0.97 ± 0$^{a, A}$	0.97 ± 0.02$^{a, A}$	0.97 ± 0.02$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$
G3-S6	0.97 ± 0$^{a, A}$	0.96 ± 0.01$^{a, A}$	0.97 ± 0.01$^{a, A}$	0.98 ± 0$^{a, A}$	0.97 ± 0$^{a, A}$	0.98 ± 0$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.23 %PM$_{2.5}$ of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	PM$_{2.5}$ (%)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	22.19 ± 1.42$^{a, A}$	36.69 ± 5.13$^{a, A}$	33.03 ± 8.16$^{a, A}$	23.08 ± 4.48$^{a, A}$	28.81 ± 3.35$^{a, A}$	32.8 ± 6.31$^{a, A}$
G1-S2	24.19 ± 10.57$^{a, A}$	36.59 ± 14.22$^{a, A}$	37.27 ± 2.65$^{a, A}$	26.36 ± 5.14$^{a, A}$	36.71 ± 5.09$^{a, A}$	33.47 ± 3.49$^{a, A}$
G1-S3	30.98 ± 3.56$^{a, A}$	31.02 ± 7.29$^{a, A}$	29.09 ± 0.54$^{a, A}$	26.95 ± 1.12$^{a, A}$	32.44 ± 2.68$^{a, A}$	37.86 ± 1.42$^{a, A}$
G1-S4	25.74 ± 0.59$^{a, A}$	33.28 ± 2.47$^{a, A}$	28.91 ± 4.52$^{a, A}$	26.18 ± 0.66$^{a, A}$	35.55 ± 4.72$^{a, A}$	36.88 ± 5.73$^{a, A}$
G1-S5	18.76 ± 1.94$^{a, A}$	31.48 ± 0.18$^{a, A}$	31.08 ± 8.62$^{a, A}$	24.86 ± 2.01$^{a, A}$	29.56 ± 10.05$^{a, A}$	29.03 ± 1.51$^{a, A}$
G1-S6	32.04 ± 4.02$^{a, A}$	27.35 ± 0.45$^{a, A}$	36.29 ± 15.81$^{a, A}$	29.45 ± 5.86$^{a, A}$	29.96 ± 6.89$^{a, A}$	29.18 ± 6.19$^{a, A}$
G3-S1	35.43 ± 12.71$^{a, A}$	31.91 ± 8.65$^{a, A}$	29.71 ± 6.73$^{a, A}$	30.08 ± 6.58$^{a, A}$	30.63 ± 4.06$^{a, A}$	27.5 ± 5.76$^{a, A}$
G3-S2	46.31 ± 2.4$^{a, A}$	32.3 ± 14.29$^{a, A}$	33.14 ± 0.78$^{a, A}$	34.32 ± 4.89$^{a, A}$	35.56 ± 7.86$^{a, A}$	27.83 ± 6.98$^{a, A}$
G3-S3	36.01 ± 9.32$^{a, A}$	41.61 ± 9.14$^{a, A}$	32.67 ± 3.36$^{a, A}$	27.07 ± 4.12$^{a, A}$	33.92 ± 0.77$^{a, A}$	35.08 ± 9.17$^{a, A}$
G3-S4	37.49 ± 9.5$^{a, A}$	31.86 ± 11.36$^{a, A}$	29.71 ± 1.29$^{a, A}$	33.54 ± 0.75$^{a, A}$	35.27 ± 13.12$^{a, A}$	33.6 ± 7.59$^{a, A}$
G3-S5	34.02 ± 15.87$^{a, A}$	29.11 ± 5.29$^{a, A}$	25.57 ± 1.82$^{a, A}$	31.59 ± 1.01$^{a, A}$	38 ± 6.74$^{a, A}$	37.72 ± 9.14$^{a, A}$
G3-S6	40.46 ± 6.6$^{a, A}$	22.17 ± 2.03$^{a, A}$	32.74 ± 6.65$^{a, A}$	33.68 ± 4.18$^{a, A}$	28.21 ± 3.76$^{a, A}$	33.11 ± 9.16$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.24 %PM$_{2.5}$ of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	PM$_{2.5}$ (%)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	31.49 ± 16.04$^{a, A}$	31.67 ± 4.17$^{a, A}$	33.66 ± 3.02$^{a, A}$	20.41 ± 0.3$^{a, A}$	29.44 ± 4.46$^{a, A}$	41.41 ± 10.75$^{a, A}$
G1-S2	41.59 ± 1.77$^{a, A}$	32.81 ± 8.25$^{a, A}$	28.18 ± 0.48$^{a, A}$	29.03 ± 8.51$^{a, A}$	32.84 ± 4.23$^{a, A}$	50.27 ± 5.89$^{a, A}$
G1-S3	33.8 ± 1.48$^{a, A}$	33.48 ± 11.99$^{a, A}$	31.29 ± 10.12$^{a, A}$	29.54 ± 16.29$^{a, A}$	37.57 ± 9.94$^{a, A}$	46.09 ± 12.88$^{a, A}$
G1-S4	31.32 ± 4.17$^{a, A}$	34.83 ± 1.77$^{a, A}$	22.19 ± 2.37$^{a, A}$	31.66 ± 2.91$^{a, A}$	37.25 ± 18.7$^{a, A}$	47.97 ± 13.89$^{a, A}$
G1-S5	34.66 ± 1.62$^{ab, A}$	35.07 ± 9.85$^{ab, A}$	27.63 ± 7.01$^{ab, A}$	22.48 ± 2.96$^{b, A}$	41.64 ± 4.65$^{ab, A}$	44.54 ± 1.69$^{a, A}$
G1-S6	32.54 ± 5.15$^{a, A}$	34.61 ± 0.18$^{a, A}$	27.21 ± 2.61$^{a, A}$	36.14 ± 18.22$^{a, A}$	29.86 ± 7.49$^{a, A}$	43.49 ± 13.8$^{a, A}$
G3-S1	26.99 ± 14.42$^{a, A}$	48.11 ± 0.01$^{a, A}$	42.07 ± 11.29$^{a, A}$	53.13 ± 5.03$^{a, A}$	40.7 ± 5.73$^{a, A}$	42.45 ± 0.3$^{a, A}$
G3-S2	51.89 ± 14.07$^{a, A}$	42.52 ± 3.66$^{a, A}$	43.37 ± 22.01$^{a, A}$	47.29 ± 3.05$^{a, A}$	40.01 ± 9.16$^{a, A}$	37.79 ± 0.23$^{a, A}$
G3-S3	42.43 ± 3.08$^{a, A}$	53.71 ± 8.39$^{a, A}$	38.71 ± 22.33$^{a, A}$	51.68 ± 4.07$^{a, A}$	43.03 ± 1.64$^{a, A}$	38.2 ± 2.16$^{a, A}$
G3-S4	39.53 ± 3.59$^{a, A}$	34.32 ± 19.2$^{a, A}$	37.23 ± 8.4$^{a, A}$	47.74 ± 5.42$^{a, A}$	29.48 ± 17.82$^{a, A}$	40.23 ± 16.05$^{a, A}$
G3-S5	43.58 ± 1.34$^{a, A}$	41.68 ± 18.14$^{a, A}$	30.88 ± 5.98$^{a, A}$	43.6 ± 8.21$^{a, A}$	27.7 ± 15.32$^{a, A}$	37.61 ± 6.38$^{a, A}$
G3-S6	44.41 ± 2.8$^{a, A}$	39.63 ± 18.06$^{a, A}$	51.72 ± 8.33$^{a, A}$	39.99 ± 14.14$^{a, A}$	42.44 ± 2.16$^{a, A}$	38.52 ± 2.6$^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.25 %PM_4 of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	PM_4 (%)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	37.5 ± 2.06 $^{a, A}$	54.36 ± 6.7 $^{a, A}$	50.58 ± 8.29 $^{a, A}$	40.34 ± 5.99 $^{a, A}$	46.98 ± 3.56 $^{a, A}$	51.74 ± 4.14 $^{a, A}$
G1-S2	40.16 ± 12.73 $^{a, A}$	53.57 ± 12.81 $^{a, A}$	54.75 ± 0.92 $^{a, A}$	43.15 ± 6.32 $^{a, A}$	54.9 ± 7.4 $^{a, A}$	51.7 ± 1.82 $^{a, A}$
G1-S3	47.32 ± 2.96 $^{a, A}$	48.64 ± 6.77 $^{a, A}$	46.22 ± 1.72 $^{a, A}$	43.35 ± 0.34 $^{a, A}$	50.02 ± 4.32 $^{a, A}$	56.78 ± 0.69 $^{a, A}$
G1-S4	42.85 ± 1.27 $^{a, A}$	50.47 ± 1.34 $^{a, A}$	46.9 ± 3.78 $^{a, A}$	42.84 ± 1.18 $^{a, A}$	54.23 ± 4.85 $^{a, A}$	55.48 ± 5.26 $^{a, A}$
G1-S5	34.27 ± 1.53 $^{a, A}$	48.79 ± 0.96 $^{a, A}$	48.71 ± 6.8 $^{a, A}$	40.48 ± 2.85 $^{a, A}$	47.39 ± 9.34 $^{a, A}$	47.4 ± 0.14 $^{a, A}$
G1-S6	49.19 ± 5.69 $^{a, A}$	44.96 ± 0.81 $^{a, A}$	53.56 ± 14.49 $^{a, A}$	48 ± 10.42 $^{a, A}$	49.37 ± 8.92 $^{a, A}$	47.94 ± 5.65 $^{a, A}$
G3-S1	53.22 ± 10.27 $^{a, A}$	51.95 ± 9.94 $^{a, A}$	48.21 ± 5.24 $^{a, A}$	50.56 ± 7.34 $^{a, A}$	50.44 ± 4.18 $^{a, A}$	48.39 ± 3.94 $^{a, A}$
G3-S2	63.76 ± 4.85 $^{a, A}$	51.57 ± 13.21 $^{a, A}$	51.98 ± 1.17 $^{a, A}$	52.11 ± 6.23 $^{a, A}$	54.3 ± 8.99 $^{a, A}$	46.31 ± 6.81 $^{a, A}$
G3-S3	57.03 ± 7.16 $^{a, A}$	59.25 ± 8 $^{a, A}$	50.17 ± 3.43 $^{a, A}$	45.32 ± 5.34 $^{a, A}$	52.32 ± 0.9 $^{a, A}$	53.85 ± 6.83 $^{a, A}$
G3-S4	58.32 ± 7.18 $^{a, A}$	51.15 ± 6.68 $^{a, A}$	47.11 ± 2.28 $^{a, A}$	53.35 ± 1.22 $^{a, A}$	54.07 ± 14.89 $^{a, A}$	52.62 ± 6.07 $^{a, A}$
G3-S5	53.34 ± 15.88 $^{a, A}$	45.86 ± 5.15 $^{a, A}$	42.96 ± 1.37 $^{a, A}$	50.54 ± 1.13 $^{a, A}$	57.73 ± 7.04 $^{a, A}$	57.52 ± 6.75 $^{a, A}$
G3-S6	59.71 ± 7.04 $^{a, A}$	39.26 ± 2.76 $^{a, A}$	51.12 ± 5.61 $^{a, A}$	53.27 ± 3.16 $^{a, A}$	48.01 ± 3.78 $^{a, A}$	53.8 ± 7.52 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.26 %PM_4 of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	PM_4 (%)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	48.06 ± 17.95 $^{a, A}$	50.74 ± 8.09 $^{a, A}$	49.67 ± 5.06 $^{a, A}$	33.41 ± 3.03 $^{a, A}$	48.08 ± 3.07 $^{a, A}$	59.55 ± 9.16 $^{a, A}$
G1-S2	60.38 ± 0.32 $^{ab, A}$	48.08 ± 8.83 $^{ab, A}$	45.41 ± 0.26 $^{b, A}$	47.81 ± 5.37 $^{ab, A}$	51.46 ± 2.42 $^{ab, A}$	66.99 ± 5.91 $^{a, A}$
G1-S3	53.72 ± 2.79 $^{a, A}$	47.75 ± 12.19 $^{a, A}$	49.09 ± 11.89 $^{a, A}$	46.36 ± 15.73 $^{a, A}$	55.63 ± 6.64 $^{a, A}$	63.11 ± 11.53 $^{a, A}$
G1-S4	49.86 ± 1.44 $^{a, A}$	50.09 ± 2.45 $^{a, A}$	38.23 ± 1.76 $^{a, A}$	51.64 ± 2.15 $^{a, A}$	55.17 ± 14.39 $^{a, A}$	64.07 ± 11.84 $^{a, A}$
G1-S5	51.64 ± 3.12 $^{a, A}$	51.04 ± 8.72 $^{a, A}$	44.99 ± 7.43 $^{a, A}$	40.88 ± 0.33 $^{a, A}$	58.42 ± 3.51 $^{a, A}$	60.21 ± 0.23 $^{a, A}$
G1-S6	51.36 ± 2.93 $^{a, A}$	51.53 ± 0.35 $^{a, A}$	43.87 ± 3.59 $^{a, A}$	54.71 ± 16.01 $^{a, A}$	47.5 ± 6.14 $^{a, A}$	62.35 ± 10.42 $^{a, A}$
G3-S1	41.93 ± 18.6 $^{a, A}$	64.79 ± 0.23 $^{a, A}$	60.3 ± 8.6 $^{a, A}$	69.79 ± 5.59 $^{a, A}$	59.49 ± 5.61 $^{a, A}$	61.35 ± 1.94 $^{a, A}$
G3-S2	69.05 ± 12.57 $^{a, A}$	58.91 ± 4.24 $^{a, A}$	60.88 ± 18.89 $^{a, A}$	65.09 ± 0.56 $^{a, A}$	57.49 ± 5.76 $^{a, A}$	57.67 ± 0.7 $^{a, A}$
G3-S3	60.26 ± 0.1 $^{a, A}$	70.13 ± 8.17 $^{a, A}$	55.19 ± 19.33 $^{a, A}$	67.93 ± 4.77 $^{a, A}$	61.15 ± 1.63 $^{a, A}$	57.35 ± 3.54 $^{a, A}$
G3-S4	57.94 ± 4.21 $^{a, A}$	50.61 ± 18.79 $^{a, A}$	56.72 ± 5.56 $^{a, A}$	65.56 ± 6.22 $^{a, A}$	44.66 ± 22.34 $^{a, A}$	59.54 ± 14.76 $^{a, A}$
G3-S5	62.31 ± 0.26 $^{a, A}$	59.52 ± 15.19 $^{a, A}$	50.28 ± 2.51 $^{a, A}$	61.58 ± 7.15 $^{a, A}$	43.61 ± 20.88 $^{a, A}$	56.12 ± 6.18 $^{a, A}$
G3-S6	62.08 ± 1.61 $^{a, A}$	56.44 ± 17.68 $^{a, A}$	67.4 ± 7.26 $^{a, A}$	59.17 ± 14.24 $^{a, A}$	60.54 ± 0.93 $^{a, A}$	56.11 ± 1.77 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.27 %PM_{10} of soybean dust collected from different sampling points of the pilot-scale front-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	PM$_{10}$ (%)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	78.56 ± 1.05 $^{a, C}$	86.78 ± 1.56 $^{a, A}$	84.88 ± 3.56 $^{a, A}$	81.38 ± 5.47 $^{a, A}$	87.63 ± 5.03 $^{a, A}$	89.32 ± 3.41 $^{a, A}$
G1-S2	79.48 ± 7.3 $^{b, BC}$	86.27 ± 7.11 $^{ab, A}$	88.74 ± 2.18 $^{ab, A}$	85.24 ± 1.34 $^{ab, A}$	89.69 ± 4.24 $^{ab, A}$	88.39 ± 3.44 $^{a, A}$
G1-S3	83.22 ± 1.25$^{b, ABC}$	86.36 ± 4.42 $^{ab, A}$	85.19 ± 2.12 $^{ab, A}$	83.64 ± 0.39 $^{ab, A}$	87.73 ± 0.46 $^{ab, A}$	91.88 ± 0.05 $^{a, A}$
G1-S4	83.01 ± 0.34 $^{a, ABC}$	87.28 ± 3.11 $^{a, A}$	86.11 ± 2.31 $^{a, A}$	83.43 ± 4.4 $^{a, A}$	90.13 ± 4.2 $^{a, A}$	91.49 ± 0.95 $^{a, A}$
G1-S5	78.75 ± 2.43 $^{a, BC}$	84.41 ± 0.74 $^{a, A}$	86.65 ± 3.44 $^{a, A}$	82.24 ± 1.85 $^{a, A}$	87.91 ± 3.71 $^{a, A}$	87.71 ± 0.66 $^{a, A}$
G1-S6	83.99 ± 3.21 $^{a, ABC}$	84.76 ± 0.4 $^{a, A}$	86.54 ± 6.88 $^{a, A}$	86 ± 6.48 $^{a, A}$	89.9 ± 3.73 $^{a, A}$	86.59 ± 0.86 $^{a, A}$
G3-S1	87.58 ± 4.21 $^{a, ABC}$	87.37 ± 4.52 $^{a, A}$	85.11 ± 4.6 $^{a, A}$	86.13 ± 3.68 $^{a, A}$	86.64 ± 3.18 $^{a, A}$	89.4 ± 0.84 $^{a, A}$
G3-S2	91.29 ± 2.11 $^{a, AB}$	87.06 ± 4.42 $^{a, A}$	87.22 ± 1.42 $^{a, A}$	87.33 ± 4 $^{a, A}$	91.2 ± 5.66 $^{a, A}$	86.87 ± 0.06 $^{a, A}$
G3-S3	89.62 ± 1.32 $^{ab, ABC}$	88.84 ± 2.49 $^{ab, A}$	84.85 ± 3.42 $^{b, A}$	85.86 ± 0.47 $^{ab, A}$	87.64 ± 0.01 $^{ab, A}$	92.52 ± 0.28 $^{a, A}$
G3-S4	92.94 ± 3.01 $^{a, A}$	87.75 ± 3.64 $^{ab, A}$	81.66 ± 0.72 $^{b, A}$	92.93 ± 1.46 $^{a, A}$	89.6 ± 1.98 $^{ab, A}$	90.08 ± 0.36 $^{ab, A}$
G3-S5	87.77 ± 3.79 $^{a, ABC}$	82.49 ± 3.17 $^{a, A}$	84.1 ± 0.59 $^{a, A}$	87.05 ± 0.8 $^{a, A}$	90.61 ± 0.04 $^{a, A}$	89.66 ± 0.33 $^{a, A}$
G3-S6	90.5 ± 1.32 $^{a, ABC}$	83.78 ± 3.37 $^{a, A}$	85.06 ± 2.34 $^{a, A}$	89 ± 1.06 $^{a, A}$	87.16 ± 1.85 $^{a, A}$	89.23 ± 1.75 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Table 3.28 %PM_{10} of soybean dust collected from different sampling points of the pilot-scale back-feed bucket elevator.

Grade (GR) - Sampling Point (SP)	PM$_{10}$ (%)					
	Run 1	Run 5	Run 9	Run 13	Run 17	Run 21
G1-S1	83.29 ± 8.84 $^{a, A}$	86.15 ± 3.44 $^{a, A}$	84.79 ± 3.97 $^{a, AB}$	74.79 ± 8.27 $^{a, B}$	87.05 ± 1.4 $^{a, A}$	91.1 ± 1.87 $^{a, A}$
G1-S2	91.17 ± 2.16 $^{a, A}$	84.83 ± 4.29 $^{a, A}$	86.34 ± 2.79 $^{a, AB}$	87.43 ± 1.08 $^{a, AB}$	88.05 ± 0.44 $^{a, A}$	91.99 ± 3.14 $^{a, A}$
G1-S3	89.75 ± 3.98 $^{a, A}$	85.53 ± 0.95 $^{a, A}$	85.81 ± 2.24 $^{a, AB}$	87.98 ± 6.34 $^{a, AB}$	88.32 ± 2.08 $^{a, A}$	91.3 ± 1.92 $^{a, A}$
G1-S4	88.53 ± 4.57 $^{ab, A}$	84.86 ± 0.87 $^{ab, A}$	80.7 ± 0.52 $^{b, B}$	88.82 ± 4.12 $^{ab, AB}$	90.86 ± 3.23 $^{ab, A}$	92.78 ± 1.81 $^{a, A}$
G1-S5	85.89 ± 2.5 $^{a, A}$	86.03 ± 1.24 $^{a, A}$	87.26 ± 1.1 $^{a, AB}$	84.77 ± 1.41 $^{a, AB}$	90.17 ± 1.34 $^{a, A}$	88.87 ± 2.06 $^{a, A}$
G1-S6	88.58 ± 1.29 $^{a, A}$	86.73 ± 1.75 $^{a, A}$	85.24 ± 3.1 $^{a, AB}$	88.72 ± 5.25 $^{a, AB}$	86.71 ± 2.76 $^{a, A}$	91.67 ± 0.7 $^{a, A}$
G3-S1	78.52 ± 13.8 $^{a, A}$	91.38 ± 1.05 $^{a, A}$	91.84 ± 0.09 $^{a, AB}$	93.15 ± 2.91 $^{a, A}$	90.73 ± 1.35 $^{a, A}$	89.64 ± 0.01 $^{a, A}$
G3-S2	92.56 ± 4.51 $^{a, A}$	87.68 ± 3.49 $^{a, A}$	89.16 ± 6.68 $^{a, AB}$	91.44 ± 0 $^{a, A}$	88.64 ± 0.4 $^{a, A}$	90.2 ± 0.62 $^{a, A}$
G3-S3	90.85 ± 1.48 $^{a, A}$	95.05 ± 3.45 $^{a, A}$	89.27 ± 3.4 $^{a, AB}$	91.96 ± 1.1 $^{a, A}$	90.07 ± 0.23 $^{a, A}$	89.21 ± 2.31 $^{a, A}$
G3-S4	89.97 ± 0.03 $^{a, A}$	86.11 ± 6.65 $^{a, A}$	90.73 ± 1.81 $^{a, AB}$	91.66 ± 1.24 $^{a, A}$	79.16 ± 14.57 $^{a, A}$	90.34 ± 3.12 $^{a, A}$
G3-S5	90.28 ± 2.2 $^{a, A}$	87.64 ± 9.09 $^{a, A}$	88.39 ± 0.53 $^{a, AB}$	90.8 ± 0.89 $^{a, AB}$	79.51 ± 15.1 $^{a, A}$	89.02 ± 0.69 $^{a, A}$
G3-S6	90.37 ± 0.22 $^{a, A}$	89.42 ± 6.91 $^{a, A}$	93.63 ± 3.16 $^{a, A}$	89.82 ± 6.05 $^{a, AB}$	90.84 ± 0.14 $^{a, A}$	87.72 ± 0.2 $^{a, A}$

Note: The same lowercase superscript indicates no significant difference across the same row ($p < 0.05$), while the same uppercase superscript indicates no significant difference across the same column ($p < 0.05$).

Chapter 4 - Influence of shape characteristics and particle size distribution of grain dust on flowability and floodability

Abstract

Dust emissions in grain handling and processing facilities are one of the most critical problems in agricultural industries. Despite research and management advancements, grain dust explosion and health concerns related to dust inhalation still exist. Dust explosions occur when the dust exceeds its minimum explosible concentration (45-150 g/m3) in the presence of confinement, oxidizing agent, dispersing agent, and ignition source. These components have long been studied and documented in the literature but studies on dust properties that affect suspension in a confined space are lacking. Two important characteristics that could influence dust dispersion and suspension are flowability and floodability. Dust samples from five grain types (wheat, corn, soybean, rice, and milo) were obtained and tested in five replicates for mean particle size, particle size distribution, and various shape characteristics (circularity, high sensitivity circularity, convexity, elongation, solidity and aspect ratio) using Morphologi G3 SE. Flowability and floodability indices were determined using Carr indices chart based on aerated and packed bulk density measurements; angles of repose, spatula, fall, and difference; compressibility; cohesion or uniformity coefficient; and dispersibility in the Hosokawa Powder Tester PT-R. Results showed significant differences in packed bulk density, cohesion, elongation, and aspect ratio among the five grain dust types. Soybean dust exhibited the highest flowability (34.70) and floodability (64.25) indices while milo dust exhibited the lowest (flowability index, 11.60; floodability index, 9.70). Very strong positive correlation was observed for floodability index and dispersibility while very strong negative correlation was observed for cohesion and flowability index. Both circularity and high sensitivity circularity strongly influenced packed bulk density, and floodability index, and moderately influenced aerated bulk density, cohesion, flowability index, angle of fall, angle of difference, and dispersibility. In terms of edge roughness, convexity significantly correlated ($p<0.05$) with all floodability and flowability parameters except packed bulk density.

Keywords: grain dust, flowability, floodability, particle size distribution, shape factors

4.1 Introduction

Moving and transferring grains across bins produce grain dust emission, which when neglected, can result in grain dust explosion and severe health hazards to workers upon exposure. There are two major causes of dust emissions in grain handling – the release of dust during material freefall, and the release of entrained air during freefall. The amount of dust released is affected by several factors including the type and effectiveness of dust collection systems, degree of enclosure in the receiving area, moisture content of the grain, quality, grade, and type of grain, and drop height (Ambrose, 2020).

Dust explosion happens when components of the explosion pentagon are fulfilled. These include fuel (combustible dust), oxidizer, ignition source, dispersion mechanism, and confinement. While most of these components are extensively studied in the past years, information on specific dust characteristics related to handling and explosion are scarce (Plumier, Zhao, Casada, Maghirang, & Ambrose, 2020). Very few studies dealt with grain dust characteristics over the years. The earliest was that of Parnell et al. (1986) where dust from sorghum, wheat, rice, corn, and soybean emitted from terminal elevators were characterized. Wade et al. (1979), Plemons (1981), Martin (1981), and Plemons and Parnell (1981) also published values of common physical properties including the mean mass diameter, particle density, bulk density, surface area, and ash content. These values are summarized in Table 1. The differences in the values presented in the table rely heavily on the method and technique involved in characterization. Wade et al. (1979) performed particle characterization using a coulter counter while Martin (1981) and Plemons (1981) used dry and wet sieving, and coulter counter techniques. From Table 1, sorghum dust has the highest mean mass diameter (36.92 µm) while corn dust has the lowest (13.70 µm).

The behavior of dust is significantly affected by particle shape (Hesketh, 1977). However, a single linear measurement is not sufficient to describe the shape of irregular and non-circular particles. The use of shape factors such as circularity, aspect ratio, and elongation provide additional information on the overall structure of particles. The majority of these shape factors may be determined using image analysis, as techniques like laser diffraction and wet dispersion can change the physical properties of the particles upon wetting (Olson, 2011). Martin (1981) associated the shapes of dust particles to surface area and particle size distribution. He used scanning electron micrographs for wheat and corn dust particles but did not publish any quantitative measure of dust shape and size. Plumier, Zhao, Casada, Maghirang, and Ambrose (2020) obtained the circularity, aspect ratio, and circle equivalent diameter of the particles of corn dust using 2D imaging. They found out that higher-quality corn samples that are freshly harvested had a higher proportion of small dust particles with a lower aspect ratio and circularity.

Other important bulk characteristics of dust related to handling are flowability and floodability. Flowability is the tendency of a powder to move from stationary to a moving state. This is affected by factors like angle of repose, compressibility, angle of spatula, and either cohesion or uniformity (Carr, 1965). Friction and inter-particle cohesion are two major particle-particle interaction forces present in most powdered materials (Crouter & Briens, 2014). Frictional forces exist between contact points and resist the relative motion of the particles. These are highly influenced by particle morphology and shape as large contact surfaces increase frictional force. Cohesion, on the other hand, describes the attraction of like particles which are held by forces such as electrostatic, electrical, capillary, and van der Waals forces. Both friction and cohesion are easily influenced by moisture. When water molecules are present between particles, they act as lubricants that reduce the friction between contacting surfaces and increase the capillary forces which make the liquid bridges between particles stronger (Shi, Fend, & Sun, 2011).

Floodability is the tendency of a powder to flood or exhibit an unstable liquid-like behavior when an aeration source is present (Diederich, Mouret, de Ryck, Ponchon, & Escadeillas, 2012). This is highly influenced by several factors like dispersibility, angle of fall, angle of difference, and flowability index (Carr, 1965). When air and powder interact through any type of crevices and cracks, including the air spaces present in rotary airlocks, the tendency of the powder to flood increases. Johanson (1998) identified some common causes of air entrapment in powders. These include powder free fall, uncontrolled air injection, back pressure from baghouses, collapsing ratholes, improper setting of permeation units, gas-solid units with gas counterflow, and use of inappropriate air pads. Among these causes, collapsing ratholes is the most common. When the hopper's walls are neither steep nor smooth enough to cause uniform flow at the walls, a rathole-type flow pattern occurs. This flow pattern causes the solids entering at a high flow rate to entrain a bubble of pressurized air which fluidizes the solids. While flushing is highly likely to occur through screw feeders, belts, and vibratory feeders, it can also occur within rotary valves. Powder free falls during bulk handling can also lead to flushing. As the powder falls from a high area to containers or hoppers, the voids present between the particles entrain air. This process accelerates as more particles reach the material surface which maintains the fluidized condition within the material bed (Johanson, 1998).

Both flowability and floodability are critical parameters in the design of bulk handling equipment for dust. As fine dust particles easily become airborne when agitated and suspended in the air for longer periods, the explosion risk associated with them is high. Quantifying the values of these properties for different grain dust types is also important for preventing other industry-related incidents such as hazardous spills and serious housekeeping problems. While there is a lot of literature that characterize various physical and engineering properties of grains and oilseeds (El Fawal, Tawfik, & El Shal, 2009; Boac, Casada, Maghirang, & Harner, 2010; Gürsoy & Güzel, 2010), there is a dearth of information on the properties of the dust produced from these grains. Hence, this study was conducted to determine the various flowability and floodability characteristics, and particle size and shape characteristics of rice, wheat, corn, soybean, and milo dust. It also aimed to determine the significant correlations that exist between specific flow, flood, and particle shape properties.

4.2 Materials and Methods

4.2.1 Sample Preparation

Grain dust samples which consist of rice, wheat, soybean, corn, and milo dust collected using a pneumatic collection system were procured from several grain handling centers in January 2021. The samples were initially sieved using air-jet sieving (Air Jet Sieve E200 LS, Hosokawa Alpine, Augsburg, Germany) to limit the particle size to at most 450 µm as this is the most explosible dust fraction (Birtwistle, 2003). After sieving, they were divided into different lots using a riffle sample divider (Riffle-Type Sample Splitter Model H-3980, Humboldt Mfg. Co., Illinois, U.S.A.). The moisture content (MC) of the samples was then determined by drying 2-3 g of samples in an air-circulating oven at 130°C for 1 hour (AACC Method 44-15.02). Since the initial MC of the dust varied from 8-12% (w.b.), the samples were stored in an environmental chamber for three weeks (RH = 55% and Temperature = 55°C) to make the MC of all dust similar. After conditioning, the final average MC of the samples was found to be 8.5% (w.b.).

4.2.2 Particle Size and Size Distribution Determination

The determination of particle size (PS) and particle size distribution (PSD) of the dust was carried out using the Malvern Morphologi G3 SE (Malvern Instruments, Malvern, U.K.). A standard sample of 3 mm^3 was prepared and dispersed on a glass slide using a sampling dispersion unit with pressurized air. The particles were imaged using a diascopic (bottom) light at 10x magnification, and standard operating procedures were created to randomly select 10,000 particles from the slide. After imaging, the size of dust particles was represented by circle equivalent (CE) diameter where a 3D image of the particle was captured as a 2D image and converted to a circle of equivalent area to the 2D image (Malvern Instruments Ltd., 2015). The

PSD was generated in both number and volume bases with focus on diameter fractions d_{10}, d50, and d_{90}, where 10, 50, and 90 represent the percentage of particles with diameters less than the specified value. Volume-based distribution differs from the number-based distribution in a way that the contribution of each particle is proportional to its volume (Malvern Instruments Ltd., 2015).

4.2.3 Particle Shape Descriptors Determination

The particle shape descriptors which include circularity (Ci), high sensitivity circularity (HSC), convexity (Co), elongation (E), solidity (So), and aspect ratio (AR) were also determined using the same equipment and procedure discussed in the previous section. Circularity determines how close a particle shape resembles a perfect circle. It has a value ranging from 0 (narrow and elongated) to 1 (perfect circle). A more sensitive measure of Ci which is sometimes referred to as compactness is the HSC. It is calculated by getting the ratio of the particle's projected area to the square of the perimeter of the particle. Like Ci, narrow-shaped rods have HSC close to 0 while a perfect circle has an HSC of 1. Another important shape descriptor is convexity, a factor that quantifies the surface roughness of a particle. It is obtained by getting the ratio of the convex hull perimeter and the actual particle perimeter. Least convex or smooth particles have Co close to 1 while irregular and spiky objects have Co close to 0 (Malvern Instruments Ltd., 2015).

Elongation and aspect ratio are shape descriptors related through the formula E=1-AR. Elongation determines how elongated a particle is while AR is used to classify the general form of particles such as fibrous, acicular, and equant (Olson, 2011). ISO 9276-6 (International Organization for Standardization [ISO], 2008) defines AR as the ratio of the Feret's minimum length to the Feret's maximum length. Both elongation and aspect ratio have values in the range

0 to 1, inclusive. Elongated particles have E values close to 1 while less elongated and more circular particles have E values close to 0. Lastly, solidity describes the overall concavity of a particle. It is calculated by dividing the area of the particle by the area of the convex hull. Like convexity, solidity is highly dependent on the convex hull. As the particle shape becomes rougher and less solid, the value of So approaches zero (Olson, 2011).

4.2.4 Flowability properties determination

The flowability properties consisting of angle of repose, compressibility, aerated bulk density, packed bulk density, angle of spatula, and either uniformity or cohesion were measured using the Hosokawa Powder Tester Model PT-R (Hosokawa Micron B.V., Japan). Each flowability property has its own setup and method of measurement. The succeeding sections discuss how each property was measured.

4.2.4.1 Angle of repose (AoR)

AoR is the steepest angle of descent relative to a horizontal plane where the material is poured to create a mound. It was measured using a set-up consisting of a stainless-steel table, small-mouthed glass funnel, and a 750-µm sieve with extension. About 100 grams of dust samples were placed into the sieve and vibrated at a frequency of 1 m/m for 180 s. The dimensions of the resulting mound were measured using a built-in laser and these were used to calculate the AoR.

4.2.4.2 Aerated (ρ_a) and packed (ρ_p) bulk densities

The aerated and packed bulk densities of the dust were measured sequentially. ρ_a was obtained first using a setup consisting of a vibration chute, steel cylindrical container with known volume, and a 750-µm sieve with extension. Similar to AoR, 100 grams of sample were placed in the sieved and vibrated at a frequency of 1 m/m until the cylinder was completely filled up with dust. A steel scraper was used to remove the excess sample from the top of the container. The final weight of the dust was measured and used to calculate the ρ_a. After this, an open-ended plastic cylindrical extension was placed on the steel cylindrical container for ρ_p determination. Additional samples were added to the sieve and vibrated until the dust filled the extension. After filling, the assembly was tapped 180 times and the new mass was determined and used to calculate ρ_p. Using the values of the two densities, the Hausner ratio and Carr's compressibility index were calculated applying Equations 1 and 2, respectively.

$$\text{Hausner Ratio} = \frac{\rho_p}{\rho_a} \qquad \text{Equation 1}$$

$$\text{Compressibility Index (\%)} = \frac{(\rho_p - \rho_a)}{\rho_p} \cdot 100 \qquad \text{Equation 2}$$

4.2.4.3 Angle of spatula (AoS)

The AoS is the angle of the powder formed on a spatula which gives a general indication of the relative angle of internal friction of a bulk material. 150 g of dust samples were poured on top of a steel spatula (5 x 7/8 in) until a mound was formed. The pan assembly was moved downwards and the angle of the mound remaining on the spatula was measured using a built-in laser. After measurement, the spatula was impacted and the angle of the material built-up was measured again. The average of the two angles before and after impact gave the dust's angle of spatula.

4.2.4.4 Cohesion and uniformity coefficient

Cohesion and uniformity coefficient are two properties used to assess the general flowability of powders. Carr (1965) stated that cohesion is used for powders with very fine particle size or those that allow measurement of an effective cohesive force. Meanwhile, the uniformity coefficient is used with powdered granular and granular materials that do not allow measurement of an effective surface cohesive force. It is obtained by getting the ratio of d_{60} (particle size where 60% of the number of particles have average diameters less than or equal to d_{60}) and d_{10} (particle size where 10% of the number of particles have average diameters less than or equal to d_{10}). Figure 1 shows a diagram of the selection process regarding the appropriate property to use for different powder types. It starts with the calculation of the mean bulk density, ρ_m (Equation 3), then comparing it with the average particle size of the dust with focus on diameters finer than 150 µm, 75 µm, and 45 µm. If the dust is coarser than these fractions, the uniformity measurement rather than cohesion measurement is performed.

$$\rho_m = \left(\frac{\rho_a + \rho_t}{2}\right) \qquad \text{Equation 3}$$

For all dust types, the mean bulk density was within the 0.4-0.9 g/cc and were less than 75 microns. Hence, the cohesion test was performed using sieve combination of 250 µm, 150 µm, and 75 µm. A standard sample size of 2 g was placed in the sieve assembly and vibrated at a frequency of 1 m/m for 60 s. After vibration, the amount of dust remaining on each sieve was weighed and rated in points (or %) which determined the percent cohesion.

4.2.4.5 Flowability index (F_{Flow})

The flowability index was determined by totaling the indices of angle of repose, compressibility, angle of spatula, and either cohesion or uniformity. The indices were then compared to Table 4.2 (Carr’s flowability index table) to determine the degree of flowability (from “very bad” to “very good”) and the necessity of bridge breaking measures (from “not required” to “special apparatus and techniques are required”).

4.2.5 Floodability properties determination

The flowability index was determined by totaling the indices of angle of repose, compressibility, angle of spatula, and either cohesion or uniformity. The indices were then compared to Table 2 (Carr's flowability index table) to determine the degree of flowability (from "very bad" to "very good") and the necessity of bridge breaking measures (from "not required" to "special apparatus and techniques are required").

4.2.5.1 Angle of fall (AoF)

The angle of fall of dust was determined immediately after the measurement of AoR. The mound was impacted three times allowing the sample to collapse. After impact, the dimensions of the resulting mound were measured by a built-in laser, and these were used to calculate the AoF.

4.2.5.2 Angle of difference (AoD)

The angle of difference was calculated by subtracting the AoF from the AoR. This property tells whether or not a powder has the characteristics of flushing during handling.

4.2.5.3 Dispersibility

Dispersibility is a direct measure of the ability of a powder to flood and be fluidized (Carr, 1965). It was measured using a separate dispersing chamber attached to the powder tester. The chamber consists of a plastic cylinder (4 in. internal diameter and 13 in. length) through which the sample is dropped onto a watch glass. The initial and final weight of the dust remaining on the watch glass after dropping were used to calculate the dispersibility. For each test, about 10 g of sample material was used.

4.2.5.4 Floodability index (F_{Flood})

Similar to the flowability index, the floodability index was calculated by summing the indices of AoF, AoD, dispersibility, and F_{Flow}. The F_{Flood} indices were then compared to Table 4.3 (Carr indices chart of floodability) to determine the degree of floodability ("won't flush" to "very high") and the necessary measures for flush prevention ("not required" to "rotary seal must be used").

4.2.6 Data analysis

All data obtained from the experiment were analyzed using Statistical Analysis Software (SAS) 9.3 (SAS Institute, Cary, NC, U.S.A.). Analysis of Variance (ANOVA) was used to compare treatment means while Tukey's Honestly Significant Difference (HSD) was used to compare significant differences ($p<0.5$) between treatment means. To determine the degree of association between particle size, size distribution, and shape descriptors to flowability and floodability parameters, Pearson's correlation procedure was performed. All tests were conducted in five replications.

4.3 Results and Discussion

4.3.1 Flowability properties

The flowability properties of five grain dust types are presented in Table 4 and illustrated in Figure 2. Corn dust exhibited the highest angle of repose (AoR, 74.08°) while rice dust had the lowest (60.20°). AoR is an indirect measure of inter-particulate friction or resistance between particles of materials. Dry particulate materials with lower AoR usually have lower flowability as determined by their inability to form a heap with steep slope. The small interparticle resistance causes the individual particles to easily roll along the heap. AoR is highly dependent on testing conditions such as moisture content and relative humidity, and the specific method of testing, hence, the general flowability of powders cannot be determined by using AoR alone (Amidon, Meyer, & Mudie, 2017). In terms of aerated (ρ_a) and packed (ρ_p) bulk densities, significant differences ($p<0.05$) were observed among the different dust types except the ρ_a of soybean and milo dust. Hassanpour, Hare, and Pasha (2019) reported that the relationship of ρ_a and ρ_p explains the degree of powder cohesiveness. Cohesive powders have lower ρ_a than ρ_p as cohesive forces resist the relative particle displacement which contribute to the mass of the loosely packed powder in the cylindrical container. Free-flowing powders, on the other hand, have higher ρ_a than ρ_p as weaker cohesive force creates more particle displacement. Among the five dust types, wheat dust had the highest bulk densities while milo dust had the lowest.

Apart from cohesiveness, compressibility is another flow property that is directly affected by aerated and packed bulk density. Wheat dust had the highest percent compressibility (51.68%) while soybean dust had the lowest (32.84%). This means that wheat dust is more compressible than soybean dust when subjected under the same normal stress. One factor that explains this behavior is the particle size. Particles with smaller mean diameters can easily fill up the voids and air spaces during compression compared to particles with larger mean diameters (Barretto, Buenavista, Pandiselvam, & Siliveru, 2021). This observation is consistent with the measured particle size of soybean and wheat dust presented in Table 4.8. The percent compressibility gives an excellent picture of surface area, deformability or friability, and uniformity in particle shapes and size. In general, less compressible powders are more flowable while more compressible powders are less flowable. There is approximately 20-21% compressibility borderline between non-free-flowing and free-flowing materials (Carr, 1965).

The angle of spatula (AoS) of wheat, corn, soybean, and milo dust did not vary significantly ($p>0.05$) among the four dust types. However, rice dust had the highest AoS (80.32°). AoS gives an indication of the relative angle of internal friction or rupture of a powder. For free-flowing materials, only one angle rupture is commonly observed while for non-free-flowing materials, multiple irregular ruptures usually develop on the powder while it is on the blade. Non-free-flowing materials also have larger AoS than AoR. In flow analysis, AoS gives a better indication of flowability than AoR since it gives an indirect measure of porosity, fluidity, uniformity, surface area, and cohesion. Values of AoS less than 40° indicates that the material is free-flowing while values greater than 40° describes a non-free-flowing material (Carr, 1965). Since all AoS values of the five dust types are greater than 40°, they all fall under the non-free-flowing category. This is also the reason why multiple irregular ruptures on all dust samples were observed during testing.

Cohesion testing in the Hosokawa Powder Tester does not measure the cohesion within the atoms but rather the apparent force of cohesion that exist between the surfaces of fine particles. From Table 4.4, significant differences ($p<0.05$) in percent cohesion were observed for all dust types, with milo dust having the highest percent cohesion (82.14%) and soybean dust having the lowest (15.86%). This explains why the particles of milo dust formed several agglomerations on the 250-μm mesh which have caused greater material retention.

Shown in Table 4.5 are the overall flowability indices (F_{Flow}) of the five grain dust types and their corresponding degree of flowability and necessity of bridge breaking measures based on Carr indices chart of flowability (Carr, 1965). Significant differences ($p<0.05$) were observed for the flowability indices of wheat, corn, soybean and milo dust (Table 4.4) with soybean dust having the highest F_{Flow} (34.70) and milo dust having the lowest (11.60). However, despite the significant difference in the flowability indices of rice and soybean dust, both values fall under the "bad" degree of flowability classification ($20 \leq F_{Flow}(bad) \leq 39$). This means that powerful measures such as aggressive agitation shall be provided in case bridging of dust occur. Meanwhile, wheat, corn, and milo dust have flowability indices that fall in the "very bad" degree category. This indicates that the F_{Flow} are within the 0 to 19 range. Under this classification, it is necessary to use special apparatus or techniques to break the dust bridging when it happens during handling.

4.3.2 Floodability properties

The floodability properties of the five grain dust types are presented in Table 6 and illustrated in Figure 3. Significant differences ($p<0.05$) were observed for the angle of fall (AoF) of rice, wheat, and milo dust while no significant difference ($p>0.05$) was observed between rice and soybean dust. The highest angle of fall was exhibited by milo dust (64.80°) while the lowest was exhibited by rice dust (51.40°). Testing the angle of fall requires impacting the heap of powder with a certain vibration or force. The application of this impact energy alters the angle of gradient of the cone which loosens the contact force between individual particles and thereby making the heap collapse. Under the same impact force, the more collapsible a powder is, the more floodable it is. Although AoF is a critical property in floodability determination, this alone does not give direct indications of floodability. It is more appropriate to determine the difference between the angle before impact (AoR) and angle after impact (AoF), which is called the angle of difference (AoD). Soybean dust exhibited the highest AoD (23.50°) while milo dust exhibited the lowest (4.40°) (Table 6). This indicates that soybean dust has the greatest tendency to flood compared to other dust types when AoD is concerned. Significant differences ($p<0.05$) were also observed for the AoD of wheat, corn, soybean, and milo dust.

Dispersibility is a direct measure of the tendency of powders to flood or be fluidized. It is always used alongside dustiness and floodability. Generally, powders that are more dispersible are those that are dustier and easily floods in the presence of aeration. Soybean dust had the highest dispersibility (46.56%) while milo dust had the lowest (4.86%). Meanwhile, no significant differences were observed for the dispersibility of rice, wheat, and corn dust which ranged from 30.70% to 36.64%.

Summarized in Table 7 are the overall floodability indices (F_{Flood}) of the five grain dust types and their corresponding degrees of floodability and measures for flushing prevention. The floodability indices ranged from 9.70 to 64.25 with milo dust having the lowest index and soybean dust having the highest. Despite non-significant differences in the indices of rice, wheat, and corn dust (Table 5), wheat dust falls under different degree of floodability than rice and corn dust. Wheat dust had a ‘may flush’ category where rotary seal is necessary under certain flow speed and feed conditions while both rice and corn dust had a ‘tends to flush’ category where the use of rotary seal is sometimes required. Soybean dust had the highest tendency to flood as signified by very high floodability index while milo dust had the lowest flooding tendency.

4.3.3 Particle size and shape characteristics

The particle size distribution (PSD) and cumulative PSD of grain dust in both number and volume bases are summarized in Table 7 and illustrated in Figures 4 to 8. The number-based distribution (nPSD) gives equal weighting of particles irrespective of the particle size while the volume-based distribution (vPSD) takes into account the volume of the particles to determine the contribution of the particle to the distribution. For image analysis and laser diffraction methods, the 10th, 50th, and 90th percentiles are often reported for easier characterization of the median of distribution, as well as the upper and lower ends of the distribution (Horiba Instruments Inc, 2010). More evident significant differences among the percentiles of nPD were observed compared to vPSD. For nPSD, soybean dust had the highest median diameter (15.34 µm) while wheat dust had the lowest (4.64 µm). The same observation is true for D[n,0.90] which suggests that soybean dust is dominated by larger particles compared to the other four grain dust types. From Figure 4, it can be observed that the distribution of rice, milo, wheat, and corn dust are unimodal while the distribution of soybean dust is bimodal. In the case of vPSD, soybean dust had the highest median diameter (35.76 µm) while corn dust had the lowest (12.01 µm). Corn dust also had the lowest D[V,0.90] while no significant differences were observed for the D[V,0.90] of rice, wheat, soybean, and milo dust.

In terms of shape characteristics, both circularity (Ci) and high sensitivity circularity (HSC) showed significant differences among the particles of rice, wheat, corn, and milo dust. The Ci values ranged from 0.83 to 0.91 with milo dust having the highest Ci, and wheat and soybean dust having the lowest. This means that the particles of milo dust are more circular (since Ci is closer to 1) compared to the particles of the other dust types. The HSC (0.79) and circle equivalent (CE) diameter (15.34 µm) of corn dust is higher than the observed mean HSC and CE diameter of corn reported by Plumier et al. (2020) which were 0.74 and 11.94 μm, respectively. For convexity (Co), no significant differences ($p>0.05$) were observed for the particles of rice, wheat, and milo dust, while significant differences ($p<0.05$) were observed for corn and soybean dust. Convexity measures the edge roughness of the particles. As the surface of a particle gets rougher, the actual particle perimeter increases, lowering the value of Co (Olson, 2011). Despite the soybean dust having the lowest Co value (0.94), all measurements are greater than 0.90 which suggests that the particles of the five dust types have smooth edges.

Significant differences were observed for elongation (E). The particles of wheat dust had the highest value of E (0.39) while the particles of milo dust had the lowest (0.20). This is consistent with the observed value of Ci as greater deviation from a perfect circle increases E. Consequently, significant differences among the five dust types were also observed for the aspect ratio (AR) as E and AR are related by the formula: $AR = 1-E$. The observed AR of corn dust (0.72) was higher than those reported by Plumier et al. (2020) which was 0.70. Despite significant differences in E, the low value (<0.4) signifies that the particles of all dust types are less elongated and more circular. In terms of the overall concavity of the particles measured by solidity (So), rice, wheat, and corn dust had the same value of 0.95. The particles of milo dust had the highest So (0.97) while the particles of soybean dust had the lowest (0.93). Similar to Co, So is highly dependent on the convex hull. As the particle becomes rougher and less solid, the value of So approaches zero. On the contrary, as the particle becomes smoother and rounder, the So value approaches one (Olson, 2011).

4.3.4 Correlation of particle size and shape characteristics to flowability and floodability

Table 9 shows the coefficient of Pearson correlation (r) between flowability and floodability parameters of grain dust. AoR significantly correlated ($p<0.05$) with ρ_a, COMP, AoS, and AoD; AoF with ρ_p, COMP, COH, F_{Flow}, AoD, DISP, and F_{Flood}; AoS with ρ_a, COMP, and AoD; and AoD with COMP, COH, F_{Flow}, DISP, and F_{Flood}. For the two densities, ρ_a significantly affected ($p<0.05$) ρ_p and COMP while ρ_p significantly affected ($p<0.05$) DISP and F_{Flood}. Very strong positive correlation ($r \geq 0.90$) was observed for FLOOD and DISP while very strong negative correlation was observed for COH and F_{Flow}. Overall, the flowability index was significantly influenced by COMP, COH, AoF, and AoD. The floodability index, on the other hand, was significantly influenced by ρ_p, COMP, COH, F_{Flow}, angle of fall, angle of difference, and dispersibility.

The Pearson correlation between flowability, floodability, and particle size and shape characteristics of the five grain dust types are shown on Table 10. Based on the number-based size distribution, D[n,0.10] significantly correlated ($p<0.05$) with ρ_a, ρ_p, AoF, DISP, and F_{Flood} while both D[n,0.50] and D[n,0.90] significantly correlated with AoR, ρ_a, ρ_p, and AoS. Meanwhile, for the volume-based size distribution, D[V,0.10] significantly correlated with AoR, ρ_a, and ρ_p; D[V,0.50] with COMP, F_{Flo} and AoD; and D[V,0.90] with AoR, COMP, COH, F_{Flow}, AoF, AoF, DISP, and F_{Flood}. Both Ci and HSC strongly influenced ρ_p, and F_{Flood} and moderately influenced ρ_a, COH, F_{Flow}, AoF, AoD, and DISP. In terms of edge roughness, Co significantly correlated ($p<0.05$) with all floodability and flowability parameters except ρ_p. The same significant correlation was observed for E and AR excluding COMP, AoS, F_{Flow}, and AoD.

Lastly, So both significantly and positively influenced ρ_p, COMP, COH, and AoF while negatively influenced $F_{Flow,}$ AoD, DISP, and $F_{Flood.}$

4.4 Summary and Conclusion

Five grain dust types (wheat, rice, corn, soybean, and milo) collected using a pneumatic collection system were used in the study. The particle size, particle size distribution, and shape characteristics (circularity, high sensitivity circularity, convexity, elongation, angle of repose, and solidity) were determined using 2D imaging while the flowability properties (angle of repose, aerated and packed bulk densities, compressibility, angle of spatula, and cohesion) and floodability properties (flowability index, angle of fall, angle of difference, and dispersibility) were measured using a powder tester. Wheat and milo dust showed greater sensitivity to tapping or agitation, implying that particle-to-particle interaction and bridging are favored during bulk handling and transportation. Among the five grain dust types, the most and least flowable, as indicated by flowability indices, were soybean dust (34.70) and milo dust (11.60), respectively.

Overall, the dust samples fall into the flowability classification ranging from “bad” to “very bad”, signifying that bridging phenomenon may happen between dust particles. Special mediating apparatus, like aggressive dust agitator, is recommended to control dust bridging during bulk handling. Based on floodability parameters such as AoD, DISP, and floodability indices, soybean and milo dusts exhibited the highest and lowest tendency to flood during handling, respectively. An appropriate prevention mechanism such as rotary seal is recommended for grain dust type with greater tendency to flood. The most circular and least elongated dust particles were measured from milo dust due to highest circularity (0.91), high sensitivity circularity (0.85), aspect ratio (0.80), and solidity (0.97). Very strong positive correlation ($r \geq 0.90$) was observed for FLOOD and DISP while very strong negative correlation was observed for COH and F_{Flow}. Overall, the floodability index was significantly influenced by

ρ_p, COMP, COH, F_{Flow}, angle of fall, angle of difference, and dispersibility while the flowability index was significantly affected by COMP, COH, AoF, and AoD.

Flowability and floodability properties of grain dust play a significant role in understanding its explosibility and handling characteristics. Meanwhile, particle size and shape characteristics are important in understanding the resulting differences between flowability and floodability properties of various grain dust types. With knowledge on these grain dust characteristics, appropriate design of explosion hazard indicator, handling and separation equipment, and other bulk handling equipment that will reduce the hazard associated with explosion and unexpected spills can be developed. Furthermore, quantitative values of dust properties are important as these provide the necessary data to construct modeling and simulation experiments of dust explosion, dust emission, handling and conveying, and the detachment of dust from the grain bulk.

4.5 References

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4.6 Tables

Table 4.1 Published physical properties of common dust types from terminal elevators

Grain Type	Mean mass diameter (µm)	Particle Density (g/cm^3)	Bulk Density (g/cm^3)	Surface Area (m^2/g)	Ash Content (Dry Basis), %
Wheat	32.97[b]	1.48[e]	0.208[e]	0.862[e]	7.19-28.5[c,e]
Corn	13.70-19.57[a,b]	1.50[e]	0.153[e]	0.826[e]	1.88-12.0[c,d,e]
Rice	21.75[b]	1.46[e]	0.22[e]	1.092[e]	30.6-31.45[d,e]
Sorghum	36.92[b]	1.43[e]	0.308[e]	0.866[e]	7.5-9.59[d,e]
Soybean	15.50-30.00[a,b,c]	1.69[e]	0.150[e]	0.869[e]	12.1-40.5[c,d,e]

[a] Wade et al. (1979) (from table 1 of Parnell et al. (1986))
[b] Plemons (1981) (from table 1 of Parnell et al. (1986))
[c] Martin (1981) (from table 1 of Parnell et al. (1986))
[d] Plemons and Parnell (from table of Parnell et al. (1986))
[e] Parnell et al. (1986) (from tables 4, 5, and 7)

Table 4.2 Carr indices chart of flowability (adapted from Carr, 1965)

Degree of Flowability	Flowability Index	Necessity of Bridge-Breaking Measures	Angle of Repose		Compressibility		Angle of Spatula		Uniformity		Cohesion	
			Degree	Index	%	Index	Degree	Index	No.	Index	%	Index
Very Good	90 - 100	Not Required	> 25	25	< 5	25	< 25	25	1	25		
			26 - 29	24	6 - 9	23	26 - 30	24	2 - 4	23		
			30	22.5	10	22.5	31	22.5	5	22.5		
Fairly Good	80 - 89	Not Required	31	22	11	22	32	22	6	22		
			32 - 34	21	12 - 14	21	33 - 37	21	7	21		
			35	20	15	20	28	20	8	20		
Good	70 - 79	Sometimes vibration is required	36	19.5	16	19.5	39	19.5	9	19		
			37 - 39	18	17 - 19	18	40 - 44	18	10 -11	18		
			40	17.5	20	17.5	45	17.5	12	17.5		
Normal	60 - 69	Bridging will take place at the marginal point	41	17	21	17	46	17	13	17		
			42 - 44	16	22 - 24	16	47 - 59	16	14 - 16	16		
			45	15	25	15	60	15	17	15	< 6	15
Not Good	40 - 59	Required	46	14.5	26	14.5	61	14.5	18	14.5	6 - 9	14.5
			47 - 54	12	27 - 30	12	62 - 74	12	19 - 21	12	10 - 29	12
			55	10	31	10	75	10	22	10	30	10
Bad	20 - 39	Powerful measures should be provided	56	9.5	32	9.5	76	9.5	23	9.5	31	9.5
			57 - 64	7	33 - 36	6	77 - 89	7	24 - 26	7	32 - 54	7
			65	5	37	5	90	5	27	5	55	5
Very Bad	0 - 9	Special Apparatus and techniques are required	66	4.5	38	4.5	91	4.5	28	4.5	56	4.5
			67 - 89	2	39 - 45	2	92 - 99	2	29 - 35	2	57 - 59	2
			90	0	> 45	0	> 99	0	> 35	0	> 79	0

Table 4.3 Carr indices chart of floodability (adapted from Carr, 1965)

Degree of Floodability	Floodability Index	Measure for Flushing Prevention	Flowability		Angle of Fall		Angle of Difference		Dispersibility	
			Degree	Index	%	Index	Degree	Index	No.	Index
Very High	80 - 100	Rotary seal must be used	> 60	25	< 10	25	> 30	25	< 50	25
			59 - 56	24	11 - 19	23	29 - 28	24	49 - 44	24
			55	22.5	20	22.5	27	22.5	43	22.5
			54	22	21	22	26	22	42	22
			53 - 50	21	22 - 24	21	25	21	41 - 36	21
			49	20	25	20	24	20	35	20
Fairly High	60 - 79	Rotary seal is required	48	19.5	26	19.5	23	19.5	34	19.5
			47 - 45	19.5	27 - 29	18	22 - 20	18	33 - 29	18
			44	19.5	30	17.5	19	17.5	28	17.5
			43	19.5	31	17	18	17	27	17
			42 - 40	19.5	32 - 39	16	17 - 16	16	26 - 21	16
			39	19.5	40	15	15	15	20	15
Tends to Flush	40 - 59	Sometimes rotary seal is required	38	14.5	41	14.5	14	14.5	19	14.5
			37 - 34	12	42 - 49	12	12	12	18 - 11	12
			33	10	50	10	10	10	10	10
May Flush	23 - 39	Rotary seal is necessary depending on flow speed and feed conditions	32	9.5	51	9	9.5	9.5	9	9.5
			31 - 29	8	52 - 56	8	8	8	8	8
			28	6.25	57	7	6.25	6.25	7	6.25
Won't Flush	0 - 24	Not Required	27	4	58	6	6	6	6	6
			26 - 23	3	59 - 64	5 - 1	3	3	5 - 1	3
			< 23	0	> 64	0	0	0	0	0

Table 4.4 Flowability properties (mean ± SD) of select grain dust types

Flowability properties	**Rice dust**	**Wheat dust**	**Corn dust**	**Soybean dust**	**Milo dust**
Angle of repose (°)	60.20 ± 1.79^{d}	65.58 ± 2.18^{c}	74.08 ± 2.29^{a}	73.44 ± 2.58^{ab}	69.20 ± 3.46^{bc}
Aerated bulk density (g/cc)	0.28 ± 0.00^{c}	0.21 ± 0.00^{d}	0.34 ± 0.01^{b}	0.36 ± 0.01^{a}	0.36 ± 0.01^{a}
Packed bulk density (g/cc)	0.54 ± 0.00^{c}	0.44 ± 0.00^{e}	0.64 ± 0.00^{b}	0.52 ± 0.01^{d}	0.69 ± 0.01^{a}
Compressibility (%)	47.42 ± 1.00^{b}	51.68 ± 0.64^{a}	47.20 ± 0.87^{b}	32.84 ± 4.02^{c}	47.74 ± 1.98^{ab}
Spatula (before impact, °)	82.06 ± 0.52^{a}	79.88 ± 0.80^{ab}	76.46 ± 0.75^{bc}	75.68 ± 4.33^{c}	77.30 ± 0.79^{bc}
Spatula (after impact, °)	78.58 ± 1.18^{a}	74.48 ± 1.46^{b}	72.28 ± 1.15^{b}	72.88 ± 3.38^{b}	75.18 ± 1.29^{b}
Angle of spatula (°)	80.32 ± 0.79^{a}	77.08 ± 0.85^{ab}	74.38 ± 0.88^{b}	74.28 ± 3.42^{b}	76.26 ± 0.81^{b}
Cohesion (%)	45.68 ± 2.41^{d}	67.78 ± 0.32^{b}	52.32 ± 2.48^{c}	15.86 ± 0.67^{e}	82.14 ± 1.02^{a}
Uniformity coefficient	3.81 ± 0.14^{cb}	3.28 ± 0.03^{c}	4.43 ± 0.58^{b}	6.33 ± 0.61^{a}	2.52 ± 0.22^{d}
Flowability index	21.00 ± 0.00^{b}	14.50 ± 1.37^{c}	18.60 ± 1.67^{b}	34.70 ± 2.22^{a}	11.60 ± 0.22^{d}

[a-e] Mean values with different superscript letters in the same row differ significantly among select grain dust types ($p<0.05$); Abbreviations: SD, standard deviation.

Table 4.5 Flowability of select grain dust types based on Carr indices chart of flowability

Grain dust type	**Flowability index**	**Degree of flowability**	**Necessity of bridge breaking measures**
Rice	21.00	Bad	Powerful measures should be provided (agitate more aggressively)
Wheat	14.50	Very bad	Special apparatus and techniques are required
Corn	18.60	Very bad	Special apparatus and techniques are required
Soybean	34.70	Bad	Powerful measures should be provided (agitate more aggressively)
Milo	11.60	Very bad	Special apparatus and techniques are required

Table 4.6 Floodability properties (mean ± SD) of select grain dust types

Floodability properties	Rice dust	Wheat dust	Corn dust	Soybean dust	Milo dust
Angle of fall (°)	51.40 ± 5.00^{c}	57.40 ± 2.84^{b}	56.24 ± 4.16^{bc}	51.46 ± 3.28^{c}	64.80 ± 2.10^{a}
Angle of difference (°)	9.74 ± 4.06^{dc}	10.36 ± 2.05^{c}	17.84 ± 4.19^{b}	23.50 ± 5.02^{a}	4.40 ± 3.00^{d}
Dispersibility (%)	36.64 ± 2.77^{b}	36.02 ± 1.31^{b}	30.70 ± 1.49^{b}	46.56 ± 7.34^{a}	4.86 ± 1.71^{c}
Floodability index	39.50 ± 16.56^{b}	37.15 ± 4.44^{b}	41.00 ± 4.57^{b}	64.25 ± 5.58^{a}	9.70 ± 3.38^{c}

$^{a\text{-}e}$Mean values with different superscript letters in the same row differ significantly among select grain dust types ($p<0.05$); Abbreviations: SD, standard deviation.

Table 4.7 Floodability of select grain dust types based on Carr indices chart of floodability

Grain dust type	Floodability index	Degree of floodability	Measures for flushing prevention
Rice	39.50	Tends to flush	Sometimes rotary seal is required
Wheat	37.15	May flush	Rotary seal is necessary (depending on flow speed and feed conditions)
Corn	41.00	Tends to flush	Sometimes rotary seal is required
Soybean	64.25	Fairly high	Rotary seal is required
Milo	9.70	Won't flush	Not required

Table 4.8 PSD and shape characteristics (mean ± SD) of select grain dust types

Size characteristics	**Rice dust**	**Wheat dust**	**Corn dust**	**Soybean dust**	**Milo dust**
PSD					
D[n,0.10]	2.04 ± 0.12^{c}	1.70 ± 0.07^{c}	3.15 ± 0.35^{b}	2.88 ± 0.33^{b}	5.64 ± 0.62^{a}
D[n,0.50]	6.33 ± 0.55^{d}	4.64 ± 0.24^{e}	11.15 ± 0.56^{c}	15.34 ± 0.48^{a}	12.53± 0.34^{b}
D[n,0.90]	16.97 ± 1.51^{c}	12.55 ± 0.56^{d}	19.45 ± 0.96^{b}	31.57 ± 1.35^{a}	20.71 ± 0.67^{b}
D[V,0.10]	12.61 ± 0.82^{bc}	10.47 ± 0.96^{d}	12.01 ± 0.51^{c}	19.31 ± 0.91^{a}	13.62 ± 0.37^{b}
D[V,0.50]	29.33 ± 1.38^{b}	28.50 ± 3.88^{b}	19.68 ± 0.97^{c}	35.76 ± 2.91^{a}	26.02 ± 2.25^{b}
D[V,0.90]	62.33 ± 2.06^{a}	61.25 ± 4.63^{a}	34.35 ± 3.78^{b}	60.08 ± 3.53^{a}	65.56± 3.69^{a}
Shape Characteristics					
Circularity	0.85 ± 0.01^{c}	0.83 ± 0.01^{d}	0.88 ± 0.02^{b}	0.83 ± 0.05^{d}	0.91 ± 0.00^{a}
HS circularity	0.74 ± 0.01^{c}	0.71 ± 0.01^{d}	0.79 ± 0.03^{b}	0.70 ± 0.08^{d}	0.85 ± 0.01^{a}
Convexity	0.97 ± 0.00^{a}	0.97 ± 0.00^{a}	0.96 ± 0.01^{b}	0.94 ± 0.02^{c}	0.97 ± 0.00^{a}
Elongation	0.35 ± 0.00^{b}	0.39 ± 0.00^{a}	0.28 ± 0.04^{d}	0.33 ± 0.07^{c}	0.20 ± 0.00^{e}
Aspect Ratio	0.65 ± 0.00^{d}	0.61 ± 0.00^{e}	0.72 ± 0.04^{b}	0.67 ± 0.07^{c}	0.80 ± 0.00^{a}
Solidity	0.95 ± 0.01^{b}	0.95 ± 0.00^{b}	0.95 ± 0.01^{b}	0.93 ± 0.02^{c}	0.97 ± 0.00^{a}

$^{a-e}$Mean values with different superscript letters in the same row differ significantly among select grain dust types ($p<0.05$); Abbreviations: PSD, particle size distribution; SD, standard deviation; D[n,0.10], number-based particle size below which 10% of the sample lies; D[n,0.50], number-based particle size below which 50% of the sample lies; D[n,0.90], number-based particle size below which 90% of the sample lies; D[V,0.10], volume-based particle size below which 10% of the sample lies; D[V,0.50], volume-based particle size below which 50% of the sample lies; D[V,0.90], volume-based particle size below which 90% of the sample lies

Table 4.9 Pearson correlation coefficient ($p<0.05$) between flowability and floodability characteristics of select grain dust types*

Property	**AoR**	**ρ_a**	**ρ_p**	**COMP**	**AoS**	**COH**	**F_{Flow}**	**AoF**	**AoD**	**DISP**	**F_{Flood}**
AoR	1.00	0.56*	0.34	-0.44*	-0.79*	-0.23	0.28	0.15	0.60*	-0.03	0.26
ρ_a	0.56*	1.00	0.75*	-0.59*	-0.43*	-0.26	0.34	0.11	0.28	-0.28	0.01
ρ_p	0.34	0.75*	1.00	0.05	-0.21	0.36	-0.32	0.50*	-0.23	-0.74*	-0.55*
COMP	-0.44*	-0.59*	0.05	1.00	0.43*	0.81*	-0.89*	0.49*	-0.69*	-0.40*	-0.68*
AoS	-0.78*	-0.43*	-0.21	0.43*	1.00	0.19	-0.31	-0.08	-0.49*	-0.07	-0.27
COH	-0.23	-0.26	0.36	0.81*	0.19	1.00	-0.97*	0.78*	-0.82*	-0.81*	-0.92*
F_{Flow}	0.28	0.34	-0.32	-0.89*	-0.31	-0.97*	1.00	-0.71*	0.79*	0.73*	0.88*
AoF	0.15	0.11	0.50*	0.49*	-0.08	0.78*	-0.71*	1.00	-0.66*	-0.78*	-0.84*
AoD	0.60*	0.28	-0.23	-0.69*	-0.49*	-0.81*	0.79*	-0.66*	1.00	0.68*	0.89*
DISP	-0.03	-0.28	-0.74*	-0.40*	-0.01	-0.81*	0.73*	-0.78*	0.68*	1.00	0.90*
F_{Flood}	0.26	0.01	-0.55*	-0.68*	-0.27	-0.92*	0.88*	-0.84*	0.89*	0.90*	1.00

Abbreviations: AoR, angle of repose; ρ_a, aerated bulk density; ρ_p, packed bulk density; COMP, compressibility; AoS, angle of spatula; COH, cohesion; F_{Flow}, flowability index; AoF, angle of fall; AoD, angle of difference; DISP, dispersibility; F_{Flood}, floodability index. *Pearson's r values (positive or negative) are found to be significant ($p<0.05$).

Table 4.10 Pearson correlation coefficient ($p<0.05$) between flowability, floodability, and particle size and shape characteristics of select grain dust types*

Property	AoR	ρ_a	ρ_p	COMP	AoS	COH	F_{Flow}	AoF	AoD	DISP	F_{Flood}
D[n,0.10]	0.33	0.71*	0.79*	-0.13	-0.25	0.38	-0.24	0.66*	-0.33	-0.78*	-0.58*
D[n,0.50]	0.74*	0.83*	0.80*	-0.29	-0.59*	-0.05	0.09	0.27	0.27	-0.34	-0.08
D[n,0.90]	0.60*	0.62*	0.70*	-0.11	-0.48*	-0.08	0.03	0.08	0.30	-0.19	0.00
D[V,0.10]	0.47*	0.46*	0.66*	0.09	-0.38	0.04	-0.12	0.67	0.39	-0.21	-0.09
D[V,0.50]	-0.05	-0.25	0.25	0.65*	0.04	0.39	-0.51*	0.69	-0.21*	-0.17	-0.27
D[V,0.90]	-0.43*	-0.34	0.32	0.88*	0.34	0.85*	-0.89*	0.46*	-0.76	-0.60*	-0.77*
Ci	0.20	0.53*	0.93*	0.29	-0.14	0.63*	-0.57*	0.67*	-0.46*	-0.46*	-0.89*
HSC	0.20	0.51*	0.93*	0.31	-0.14	0.64*	-0.59*	0.69*	-0.48*	-0.48*	-0.88*
Co	-0.58*	-0.51*	0.13	0.91*	0.50*	0.84*	-0.90*	0.45*	-0.80*	-0.80*	-0.53*
E	-0.41*	-0.77*	-0.96*	0.02	0.31	-0.40*	0.31	-0.61*	0.26	0.26*	0.80*
AR	0.41*	0.77*	0.96*	-0.02	-0.31	0.40*	-0.31	0.61*	-0.26	-0.26*	-0.80*
So	-0.22	-0.05	0.56*	0.71*	0.16	0.90*	-0.88*	0.69*	-0.76*	-0.76*	-0.83*

Abbreviations: AoR, angle of repose; ρ_a, aerated bulk density; ρ_p, packed bulk density; COMP, compressibility; AoS, angle of spatula; COH, cohesion; F_{Flow}, flowability index; AoF, angle of fall; AoD, angle of difference; DISP, dispersibility; F_{Flood}, floodability index; D[n,0.10], number-based particle size below which 10% of the sample lies; D[n,0.50], number-based particle size below which 50% of the sample lies; D[n,0.90], number-based particle size below which 90% of the sample lies; D[V,0.10], volume-based particle size below which 10% of the sample lies; D[V,0.50], volume-based particle size below which 50% of the sample lies; D[V,0.90], volume-based particle size below which 90% of the sample lies; Ci, circularity; HSC, high sensitivity circularity; Co, convexity; E, elongation; AR, aspect ratio; So, solidity. *Pearson's r values (positive or negative) are found to be significant ($p<0.05$)

4.7 Figures

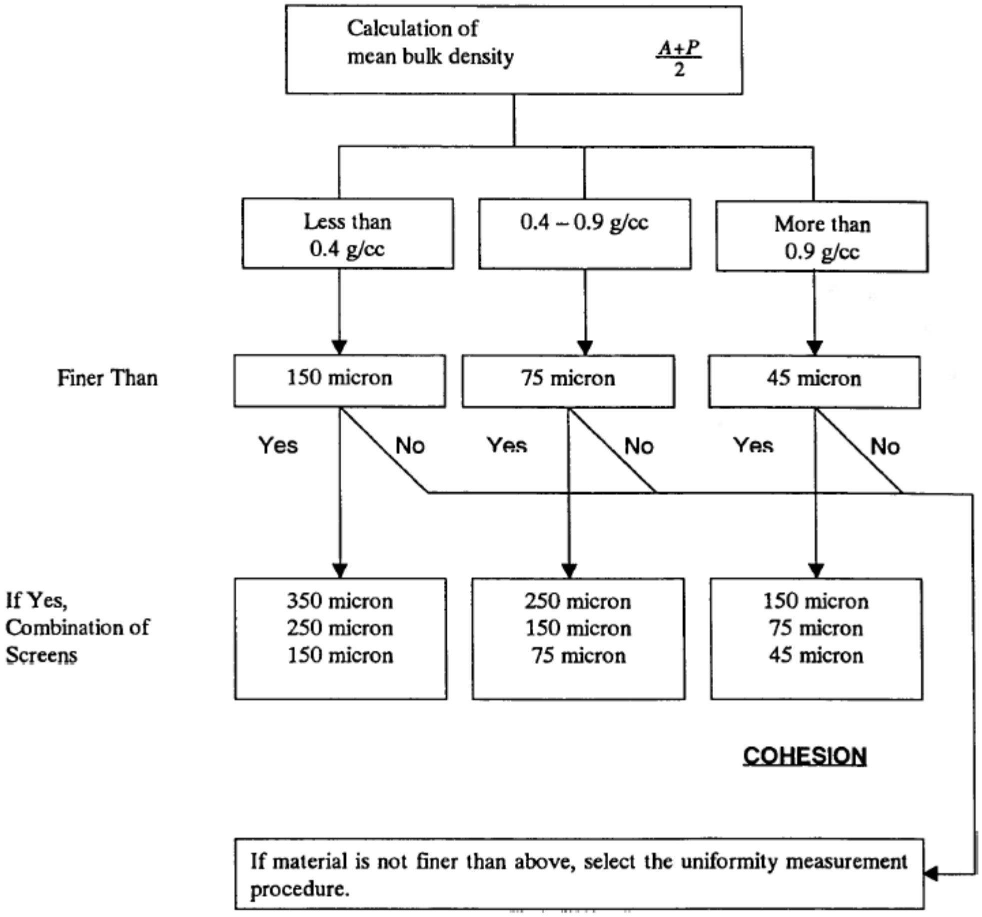

Figure 4.1 Selection of cohesion or uniformity (Carr, 1965)

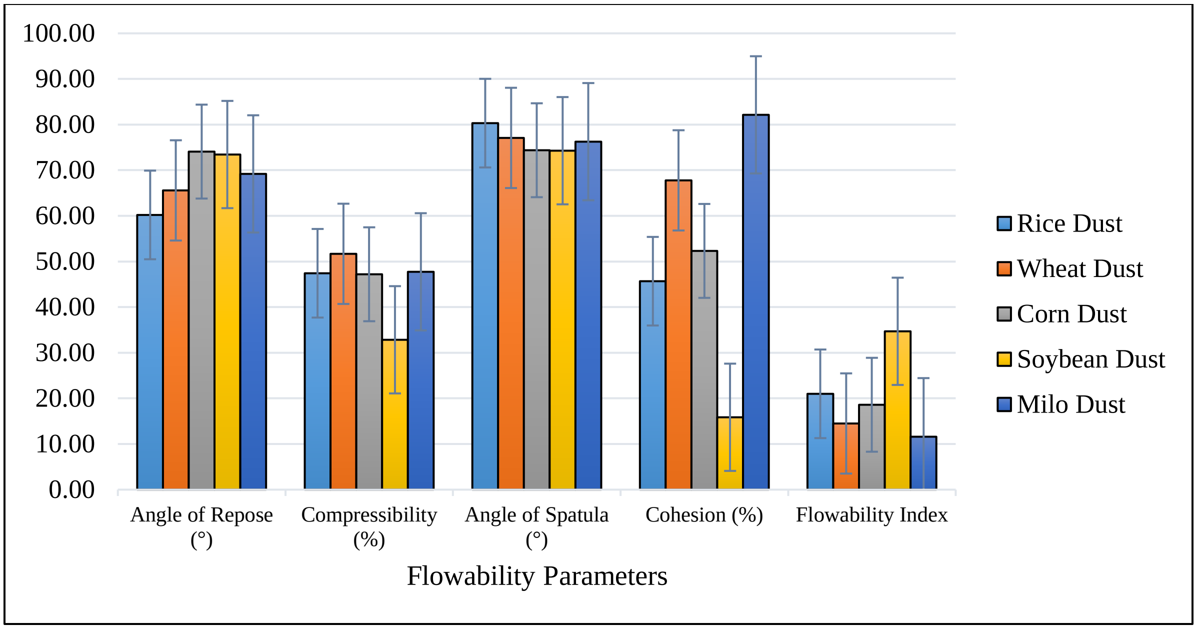

Figure 4.2 Flowability characteristics of rice, wheat, corn, soybean, and milo dust

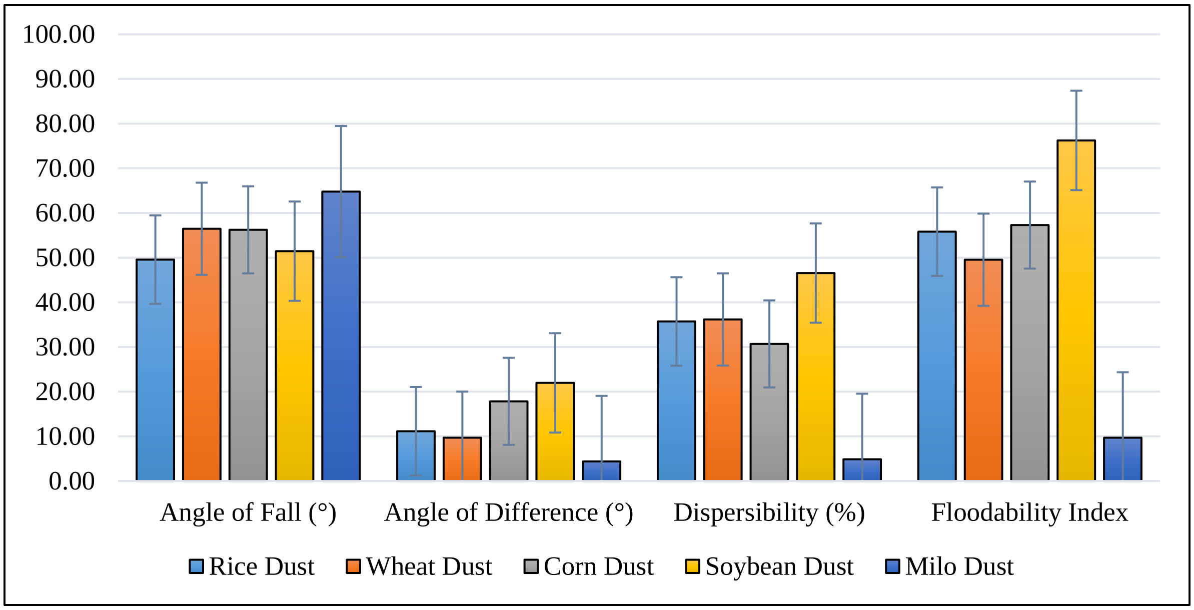

Figure 4.3 Floodability characteristics of rice, wheat, corn, soybean, and milo dust

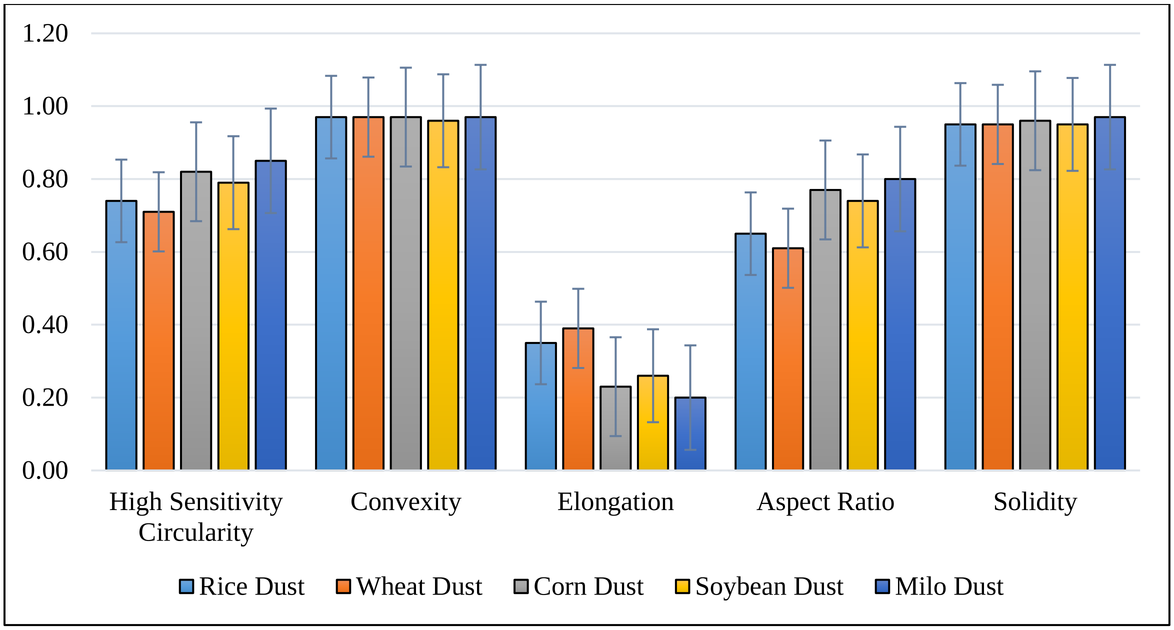

Figure 4.4 Select shape characteristics of rice, wheat, corn, soybean, and milo dust

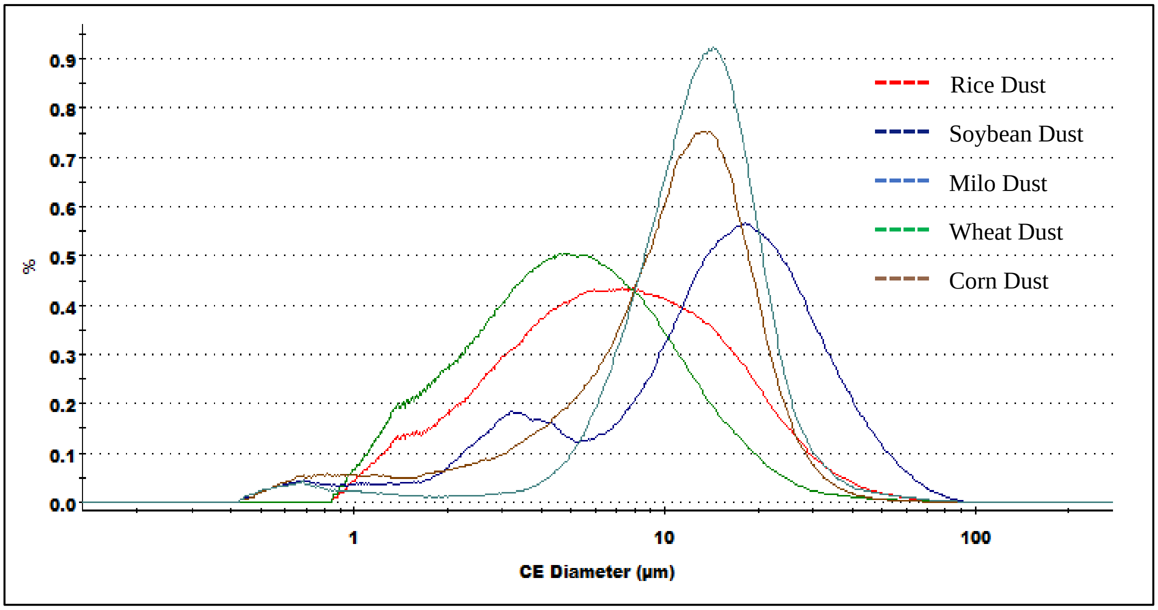

Figure 4.5 Number-based particle size distribution curve of rice, wheat corn, soybean, and milo dust.

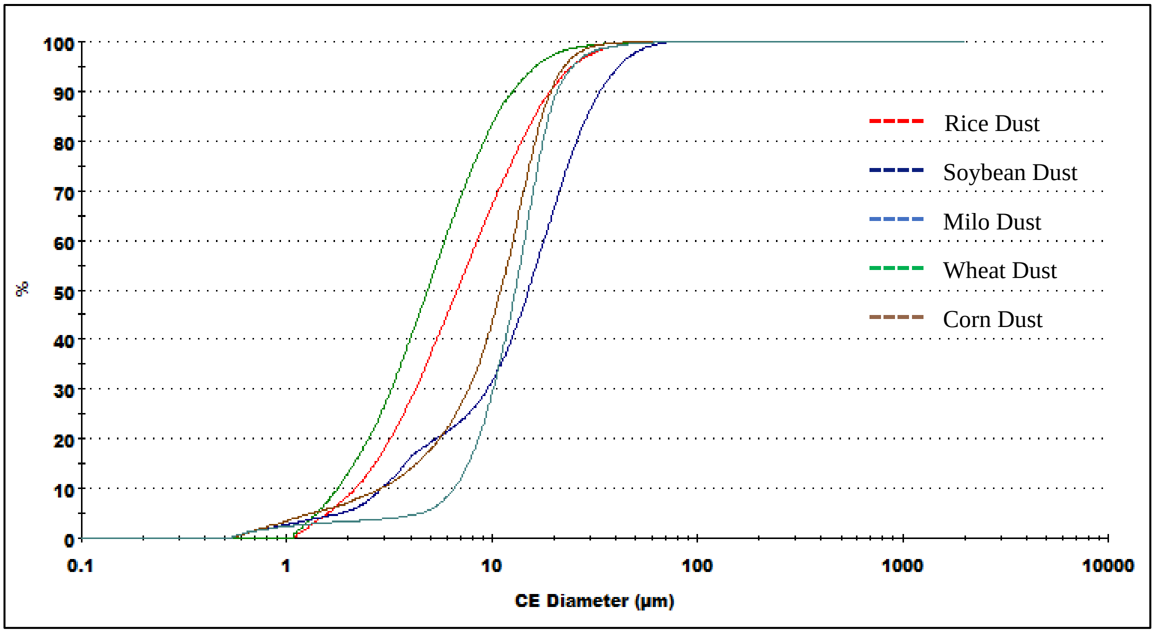

Figure 4.6 Number-based cumulative particle size distribution curve of rice, wheat corn, soybean, and milo dust.

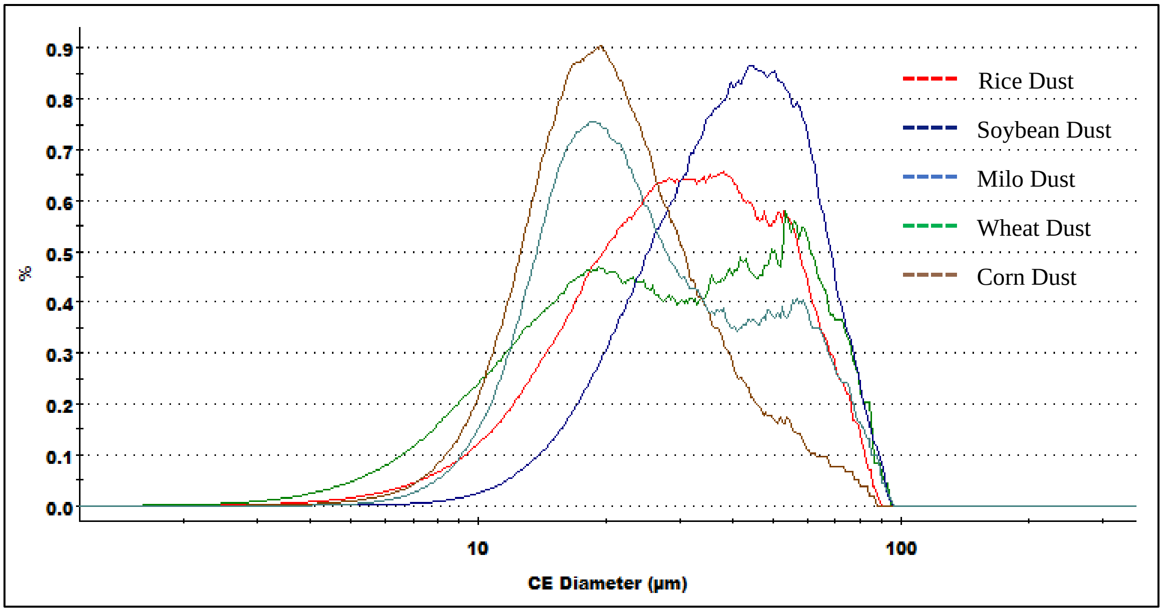

Figure 4.7 Volume-based particle size distribution curve of rice, wheat corn, soybean, and milo dust.

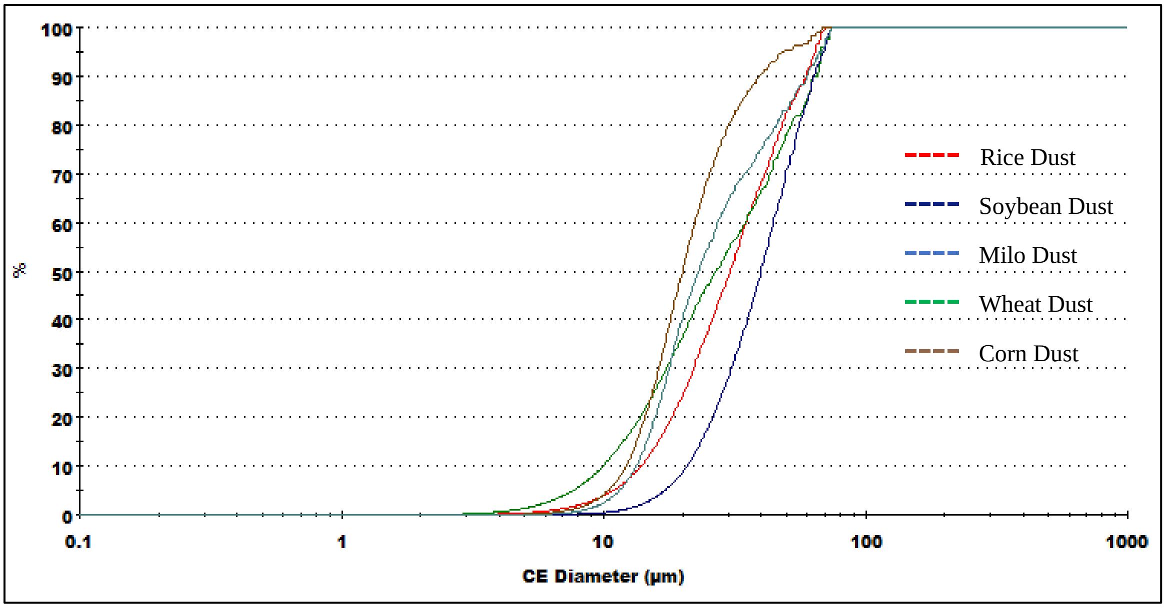

Figure 4.8 Volume-based cumulative particle size distribution curve of rice, wheat corn, soybean, and milo dust.

Chapter 5 - Summary and Recommendations

5.1 Summary

This study was conducted with the aim of understanding how the quantity and characteristics of soybean dust is affected by repeated elevator handling, grade of soybeans, and elevator types. It also aimed to provide quantitative values of flowability and floodability characteristics for future modeling studies. The following are the summary of results obtained from this study:

- A general decreasing trend in the weight of dust collected across all sampling points and runs for both front-feed and back-feed elevators and soybean grades 1 and 3.
- The overall particle size distribution of soybean dust across grades, runs, and sampling point did not significantly vary ($p>0.05$).
- The following size and shape characteristics data of soybean dust collected from repeated elevator handling were obtained – CE diameter (3.00 to 8.36 µm), D[v,0.01] (5.45 to 14.69 µm), D[v,0.05] (11.00 to 21.35 µm), D[v,0.09] (21.43 to 67.16) HS circularity (0.70 to 0.84), aspect ratio (0.65 to 0.73), elongation (0.27 to 0.25), solidity (0.92 to 0.98), and convexity (0.95 to 0.99).
- For both front-feed and back-feed elevators, significant differences ($p<0.05$) in the weight of the collected dust across grades were only observed in the first run. During the last run, the differences were not significant anymore ($p>0.05$).
- The percentage of $PM_{2.5}$ and PM_4 did not significantly differ ($p>0.05$) among soybean dust generated from different grade-sampling point combinations transferred through the front-feed elevator up to 21 runs.

- The floodability index was significantly influenced by packed bulk density, compressibility, cohesion, flowability index, angle of fall, angle of difference, and dispersibility while the flowability index was significantly affected by compressibility, cohesion, angle of fall, and angle of difference.
- Soybean dust exhibited the highest flowability index (34.70) which makes it the most flowable among the four dust types. Milo dust, on the other hand, exhibited the lowest flowability index (11.60) which makes it the least flowable.
- Soybean dust had the highest floodability index (64.25) and milo dust had the lowest (9.70). This means that soybean dust has the highest tendency to flood during handling that is why the use of rotary seal is highly recommended.
- The particles of milo dust had the highest circularity (0.91), high sensitivity circularity (0.85), aspect ratio (0.80), and solidity (0.97).
- Very strong positive correlation ($r \geq 0.90$) was observed for floodability index and dispersibility while very strong negative correlation was observed for cohesion and flowability index.

5.2 Recommendations

The following are the recommendations for further studies:

1. The soybean grades are limited to U.S. grade numbers 1 and 3 only. It is recommended to use other grades including sample grades to determine if these will have a significant effect on the amount of dust generated.
2. The repeated handling experiment utilized a pilot-scale bucket elevator leg without a pneumatic dust collection system. Hence, the percentage of the dust collected relative to the total amount of dust was not known. It is recommended to incorporate a pneumatic

dust collection system to compare the results to the observations obtained from this study and to existing literature.

3. The five grain dust types used in the second study were not collected in a standard manner. Although all samples were collected using a pneumatic collection system, the type of system used and the operating conditions during sampling collection may have impacted the quality of the samples. A more standardized method of sample collection is recommended to minimize the nuisance effect brought by the differences in sampling methods.
4. The determination of particle size, particle size distribution, and shape characteristics were all carried out using 2D imaging. It is well-known that different methods of size characterization often led to different results. The use of other particle sizing methods such as laser diffraction, wet dispersion imaging, and rotary sieving is recommended to determine the differences and similarities brought by each method.
5. The measurement of flowability and floodability properties of the dust in the Hosokawa Powder Tester only gives values for static conditions. In actual grain and dust handling operations, both grains and dust experience dynamic forces caused by moving and transferring large quantities. To determine the characteristics in dynamic situations, the use of a powder rheometer is highly recommended.