Effect of vane shape and fertilizer product on spread uniformity using a dual-disc spinner spreader

by

Ravinder Kaur Thaper

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 2, 2014

Keywords: Fertilizer Spreader, Application, Vane, Segregation, Disc, Blended Fertilizer

Approved by

John P. Fulton, Chair, Associate Professor of Biosystems Engineering
Timothy P. McDonald, Associate Professor of Biosystems Engineering
Oladiran O. Fasina, Professor of Biosystems Engineering
C. Wesley Wood, Professor and Director, University of Florida West Florida Research and Education Center

ABSTRACT

Advancements in granular applicators are required in order to provide accurate metering and placement of fertilizer as emphasis grows on nutrient and associated environmental stewardship. Spinner-disc spreaders are commonly used to apply granular fertilizers with current spread widths up to 30 m. Spreader hardware components (divider, spinner disc and vanes) influence material distribution but increased spread widths have increased the risk for non-uniform application of nutrients. Therefore, the objectives of this research were to 1) evaluate the impact of vane design on fertilizer particle behavior and spread distribution uniformity for a dual-disc spinner spreader, 2) compare and contrast physical and chemical methods for measuring nutrient concentration of blended fertilizer samples and 3) determine the segregation potential of a blended fertilizer applied using a dual-disc spinner spreader while varying feed rate and disc speed. Two types of testing were conducted; stationary and standard pan testing. A typical fertilizer dual-disc spreader was used in this study. Treatments included feed rates of 224 and 448 kg ha^{-1} and three spinner-disc speeds, 600, 700 and 800 rpm. Four vane designs were also evaluated. Results indicated that two distinct patterns of the overall spread pattern existed due to controlled and uncontrolled flow of fertilizer off the vanes. Further, vane design impacted spread uniformity. The top edge of Vane 2, tapered at 15° backwards, reduced ricocheting by approximately 50% compared to Vane 1. Vane 2 also produced the most consistent spread uniformity compared to other three vane designs over the varying disc speeds.

Vane 4, with an enclosed U-section, generated the maximum effective spread width of 24.4 m at a spinner disc speed of 800 rpm versus 22.9 m for Vanes 1, 2 and 3. Overall, Vane 2 was recommended for fertilizer application using this dual-disc spinner spreader. The chemical method for analyzing nutrient concentration generated consistently lower nutrient concentration values for P_2O_5 and K_2O compared to a physical separation method. The mean difference between the methods was a factor of 1.15. Distinct nutrient patterns were generated for the different blended fertilizer constituents; “W” shape for P_2O_5 and “M” for K_2O regardless of feed rate and spinner disc speed. Nutrient spread distribution patterns did not vary with feed rate ($p>.05$) whereas the increase in spinner disc speed caused significant differences ($p<.0001$) as the pattern widened as speed increased. DAP particles travelled farther than potash with maximum transverse distance of 16.4 m at 800 rpm.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank God who gave me strength and courage to succeed. I would like to express my deepest gratitude to my committee chair Dr. John P. Fulton who gave me this valuable opportunity. I am in debt to him for his constant support and expert advice throughout the learning process. Without his guidance and encouragement, this thesis would not have been possible. I appreciate the feedback from my committee members Dr. Timothy McDonald, Dr. Oladiran Fasina and Dr. C. Wesley Wood whose valuable comments have been illuminating. Special thanks go to Greg Pate and his farm crew who allowed me to conduct my experiments at E.V. Smith Research Center, Shorter, AL. I would also like to thank everyone in the Biosystems Engineering Department who helped during my project; especially Dewayne "Doc" Flynn, Christian Brodbeck and Joy Brown. I would also like to thank Ms. Brenda Wood for her assistance during laboratory work. I am speechless, and don't have any words to thank my mother and late father who always inspired me in my life. My father will be there in my thoughts forever, he always tried to extract the best of me through all the odds in my life, "love you so much my sweetest daddy". My mother has been an inspiration and will always be in my life. Finally, I would like to thank my husband who has always stood by me through all the ups and downs. I take this opportunity to thank my friends Simerjeet Virk, Jonathan Hall, David Herriott, Tyler Phillips, Jarrod Litton, Bruce Faulk, William Graham, Aurelie Poncet, Oluwatosin Oginni, Oluwafemi Oyedeji and Ryan McGehee.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CV	coefficient of variation
DAP	diammonium phosphate
kg m^{-3}	kilograms per cubic meter
kg ha^{-1}	kilograms per hectare
K_2O	potassium oxide
m	meter
mm	millimeter
m s^{-1}	meter per second
P_2O_5	phosphorous oxide
rpm	number of rotations per minute

Chapter 1 INTRODUCTION

1.1 Introduction

The world population continues to increase and is predicted to reach 9.15 billion by the year 2050 (FAO, 2012). Concurrently, the middle class is growing in number worldwide and expanding their diet to include meat (Delgado, 2003) increasing the demand of feed and thereby grain crops to support animal production. The economies and social classes are also growing in developing countries placing additional demand on food production to support the world population. With the increase in world population and preferred diets, it is projected there needs to be an increase of 60% to 110% in food production by the year 2050 (Science Daily, 2013) in order to match worldwide demand (fig. 1.1).

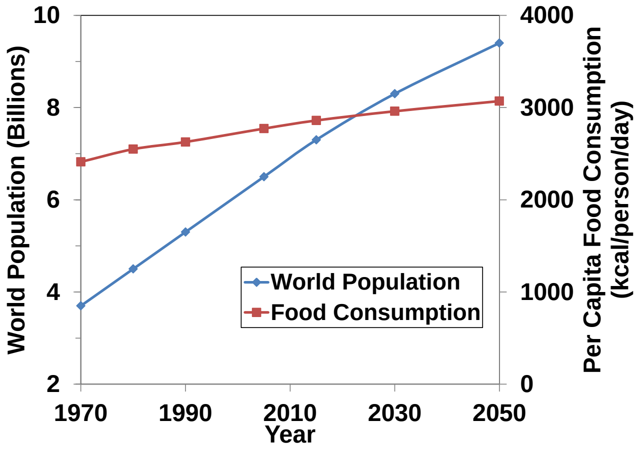


Figure 1.1. Comparison of world population and corresponding food demand from 1970 through projections for 2050 (FAO, 2012).

The three primary options for increasing the world's food production are: 1) increase the amount of cultivated lands, 2) increase crop yields on existing lands being used for production, or 3) a combination of both. At the global scale, crop production has been found to increase by 30% to 50% as a result of fertilization (Stewart et al., 2005). It has been reported that sustained yield growth is impossible without the use of fertilizer (Larson and Frisvold, 1996). Fertilizers are required for optimum crop growth providing crops the necessary nutrients. They replace soil nutrients consumed by prior crops and are responsible for 40% to 60% of world’s food supply (Borlaug, 2008). Thus, worldwide fertilizer use continues to increase and expected to reach 199 million tons by 2030 (Liederke, 2008). The U.S. ranks second with 14.9% of the world’s total fertilizer consumption with an annual usage of 21 million tons (USDA, 2010).

Fertilizer prices have also increased over time (fig. 1.2) with limited expansion of agricultural lands in the future. The judicious use of fertilizers to minimize application in environmentally sensitive areas and avoid over-application is required today at the farm level. Excess usage of fertilizers can result in surface run-off or leaching into ground and subsurface water bodies causing environmental risks. Hence, the agriculture sector must improve fertilizer usage including the placement and metering accuracy in order to minimize off-target or uneven distribution. From an application perspective, spread uniformity and application accuracy is required on modern application equipment to ensure sound nutrient stewardship for crop and pasturelands.

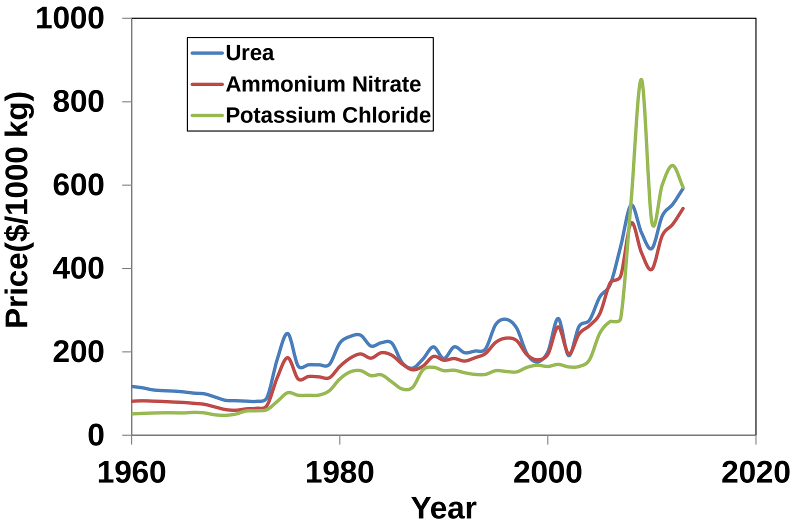


Figure 1.2. U.S. fertilizer prices since 1960 (ERS-USDA, 2012).

In the U.S., dual-disc spinner spreaders are commonly used to apply granular fertilizers and lime since they have large spread widths and inexpensive (Oleislagers et al., 1996) compared to other application equipment. For these types of large spreaders used on farms, fertilizer is dropped onto two rotating spinner discs from a conveyor chain or belt with particles accelerated by vanes mounted on the discs for distribution onto the ground. Spinner disc speed is the primary control of spread width, with 600 to 800 rpm being common to generate widths between 18.3 and 30.5 m. Hofstee and Huisman (1990) determined that a correlation existed between spread uniformity and fertilizer quality. Main factors that affect spread uniformity can be categorized into spreader hardware design and fertilizer physical properties. Spinner disc spreaders can be sensitive to variations in material flow rate, physical characteristics of fertilizers such as size, shape and friction coefficient, wind disturbances, field terrain and vibrations (Moshou et al., 2004). Tissot et al. (2002) indicated that modern agriculture requires applicators perform well in order to optimize fertilizer use. Uneven application can lead to reduced crop yield and reduction in agronomic efficiency of fertilizers. Non-uniform distribution causes the greatest financial losses (Richards, 1985), whereas errors in application rates affect crop yield and over-application increasing the risk of environmental impacts.

1.2 Justification

Food, fiber, feed and fuel production plus preserving our natural resource base such as having clean water are important for the global population. Crop production must increase in order to provide the necessary food for future generations but production should be conducted in a sustainable manner. Today, off-site transport of nitrogen (N) and phosphorous (P) must be minimized or eliminated from agricultural lands. However, fertilizer supplying the proper crop nutrition is required for maximizing crop yields and farm profitability while sustaining the production of food, fiber, feed and fuel worldwide. Therefore, applying fertilizer must be conducted in a manner with environmental stewardship at the forefront. Further, input stewardship includes efficient nutrient utilization for effective nutrient uptake by crops and pastures.

Over-application of fertilizers can potentially impact the environment by polluting waterways and underground water supplies due to surface run-off or leaching, respectively. To help promote and improve fertilizer stewardship, the fertilizer industry developed the 4Rs to nutrient stewardship program. The 4Rs to nutrient stewardship emphasizes maintaining the right source, right rate, right time and right place of fertilizers (Garcia, 2012). Today’s goal related to nutrient management is to increase crop production while enhancing environmental stewardship. Fertilizer spread uniformity and accuracy is a key focus during application. Fertilizers are expensive so they must be used judiciously. Precision agriculture (PA) technologies such as rate controllers permit accurate metering of fertilizers whereas guidance technology reduces overlap and thereby over-application of inputs. Automatic guidance allows spreaders to traverse the same field path during subsequent applications, thus coupling the risk of uneven soil fertility levels if non-uniform distribution of fertilizer occurs. All of these points together can generate varying soil fertility levels which cannot be afforded by today's farmers.

Dual-disc spinner spreaders remain a common fertilizer applicator in the U.S. In terms of area covered per year, spinner spreaders significantly cover more acres for applying fertilizer and lime than other types of applicators. The spreader parameters which influence performance including material distribution are vane, spinner disc and flow divider design along with conveyor design and gate height. It is important that they are designed to maintain accurate metering and placement of fertilizers. Vane shape is considered a significant component of spinner spreaders as it controls the effective spread width along with material distribution by impacting particle flow behavior on the spinner discs and exit point off the vane/disc assembly. From a design perspective, "controlled" material flow by the spreader hardware provides the ability to uniformly apply fertilizer whereas "uncontrolled" behavior generates a state where the spreader hardware is unable to distribute fertilizer properly. In other words, controlled fertilizer conveyance and distribution on a spinner spreader is desired and allows for calibration to deliver product accurately and uniformly. Limited research exists documenting the effect of vane design on particle flow behavior and spread uniformity for dual disc-spinner spreaders.

In summary, poor and inaccurate application of fertilizers can increase environmental and farm profitability risks. One issue is that poor spread uniformity could lead to streaking of soil fertility levels potentially impacting crop yields. Segregation could occur when applying blended fertilizers using modern spinner spreaders especially considering the large spread widths (e.g. 27.4 to 34.5 m) being used today. Therefore, this research investigates the ability to enhance spread uniformity of dual-disc spinner spreaders in order to minimize issues during application of granular fertilizers and meet performance expectations by farmers implementing new strategies such as site-specific management (SSM) of nutrients.

1.3 Objectives

The goal of this research focused on enhancing the spread uniformity of dual-disc, fertilizer spreaders to improve placement of nutrients. The overall research objectives were to:

1) Evaluate the impact of vane design on fertilizer particle behavior and spread distribution uniformity for a dual-disc spinner spreader.
2) Compare and contrast physical and chemical methods for measuring nutrient concentration across the swath width when applying a blended fertilizer.
3) Determine the segregation potential of a blended fertilizer applied using a dual-disc spinner spreader while varying feed rate and disc speed.

1.4 Organization of Thesis

Chapter 1 provides an introduction to this research along with justification and overall objectives. Chapter 2 presents a review of literature detailing information on fertilizers and various factors impacting application using dual-disc spreaders. Chapter 3 is written in manuscript format and covers the effect of vane design on fertilizer particle flow behavior and spread distribution for a dual-disc spinner spreader. Chapter 4 outlines the differences between chemical analysis and manual physical methods for determining nutrient concentration across the swath width for a blended product. Potential of segregation in a blended fertilizer application while using dual-disc spinner spreaders with variation in feed rate and disc speeds is covered in Chapter 5. Finally, Chapter 6 summarizes this research highlighting overall conclusions and future research suggestions.

Chapter 2 LITERATURE REVIEW

2.1 Fertilizers for Crop Production

Soil nutrients are essential for crop production and represent a vital component for sustainable agriculture. Fertilizer provides a source of nutrients and is required for optimal crop growth. Soils contain natural reserves of nutrients but a majority of them can remain unavailable to plants during the growing season. As plants grow, they extract nutrients from the soil and if not replenished, crop growth and yield will be negatively impacted. Fertilizers are supplied prior or during the growing season. In the US, spinner disc spreaders are commonly used to apply granular forms of fertilizers but can pose concerns relative to accurate placement and uniform distribution across cropped fields and pastures. The following information provides details on fertilizer types along with their physical and chemical properties with an overview of spinner-disc spreaders and those factors which impact spread quality.

2.2 Fertilizers and Properties

Commonly used granular fertilizers in agriculture contain three basic macro-nutrients; nitrogen (N), phosphorous (P) and potassium (K). Nitrogen is a structural component of proteins, DNA and enzymes which are required for healthy growth of plants. Phosphorous is also a structural component of DNA and helps in energy storage, conversion, stem development and a strong root network. Potassium aids in stem development and strong root network as well as promotes flower production which increases crop yield (Shakhashiri, 2014).

Fertilizer sources can be classified into two categories 1) inorganic and 2) organic. Organic fertilizers are derived from natural sources like plant and animal wastes. In the U.S., most organic fertilizers used in crop production are animal manures, swine, beef, dairy and poultry (Weekend Gardener, Monthly Web Magazine, 2014). These fertilizers normally require microbial activity in order for nutrients to become plant available. Organic fertilizers enhance biological activity in the soil and improve soil health over long term. However, insufficient amounts of organic fertilizers exist in the US to supply the needed crop nutrients on an annual basis. Therefore inorganic fertilizers are required and make up the primary source of nutrients in US farming.

Inorganic fertilizers are manufactured, synthetic sources of nutrients. Mined deposits of phosphate rock and potash are processed in fertilizer manufacturing plants to produce the required grades of nutrients containing nitrogen, phosphorous or potassium in fertilizers ready to field apply. In some cases as with potash, it is mined and simply processed through crushing to the appropriate particle size. Inorganic fertilizers are soluble with nutrients immediately available to growing plants. They generally are required in small amounts as they contain high nutrient concentrations (Chen, 2006). Inorganic fertilizers supply deficient nutrients in the soil rapidly for crops. They can also be formulated to specific crop needs. Applied fertilizer helps increase yields and biological activity in the soil (Haynes and Naidu, 1998). Inorganic fertilizers are generally applied as a single product (Table 2.1), in a blended form or as a liquid solution (Hart, 1998).

Table 2.1. Common individual fertilizer sources and their nominal concentration levels (Fert. Technologies, 2011).

Material	Nutrient Concentration N- P_2O_5-K_2O-S (%)
Ammonium nitrate	34-0-0-0
Ammonium sulfate	21-0-0-24
Urea	46-0-0-0
Diammonium phosphate (DAP)	18-46-0-0
Triple Super Phosphate (TSP)	0-46-0-0
Muriate of potash (KCl)	0-0-60-0

Based on the nutrient concentration (N-P_2O_5-K_2O), fertilizers are commonly referred to as single product fertilizers or multiple nutrients. As an example, muriate of potash (0-0-60) contains only one macronutrient; potassium thereby called a single product. Therefore, potash contains 60% K_2O. DAP (18-46-0) on the other hand includes both nitrogen and phosphorous therefore termed a multi-nutrient fertilizer. As an example ammonium sulfate is 21% nitrogen and 23% sulfur.

Blended fertilizers are used since they supply more than one nutrient source. Common examples of blended fertilizers are 13-13-13, 20-20-20, and 10-26-26 which are produced using a combination of single products as those listed in Table 2.1. The term blended is used to describe the formulation process where major fertilizer components nitrogen (N), phosphorous (P) and potassium (K) occur in separate particles, but are mechanically mixed or blended without chemical reaction to form a desired nutrient ratio. Blends can be specifically manufactured or mixed in accordance to specific soil and crop needs. Blended fertilizers have several advantages compared to single product fertilizers. A range of different products can be produced by using only basic materials (Formisani, 2005). Application of fertilizers in blended form is economical as it helps in reducing the number of passes across fields in comparison to single product fertilizer application (Yule and Pemberton, 2009). The process of blending offers flexibility in providing a range of nutrient concentrations (Miserque and Pirard, 2004). Bulk blending provides a practical and cost effective way to produce maximum crop yields. As a result, bulk blends constitute around 70% of the total granular fertilizers sold in the US (Formisani, 2005).

Fertilizers may also contain other nutrients, called micro-nutrients, such as sulfur (S), iron (Fe), boron (B), zinc (Zn) and molybdenum (Mo). Micronutrients are essential for crops but are taken up by plants in small quantities. As an example zinc is required for protein synthesis in plants for seed production and maturity. Likewise, iron aids in chlorophyll formation in plants. These micro-nutrients are added as additional nutrients or may be constituents (impurities) remaining in the fertilizer material following mining and manufacturing processes.

Liquid fertilizers also exist as nutrient sources for crops. Generally, these fertilizers are applied using sprayers or side-dress units. These fertilizers are quickly absorbed by plants and boost plant growth. Nutrients are either soil absorbed for plant root uptake or absorbed foliarly. Urea Ammonia Nitrate (UAN) is commonly used liquid fertilizer. For the research at hand, granular fertilizers and the application of them are the focus. Therefore, liquid fertilizers and their properties will not be discussed.

2.2.1 Bulk Physical Properties of Granular Fertilizers

The physical properties of granular fertilizers vary between different products but also within a single product. This variation occurs depending on the origin of the product, type of manufacturing process the fertilizer underwent, handling (Hoffmesiter et al., 1964), storage and transportation. Physical properties and their variation influence conveyance, storage, transportation and application of fertilizers.

2.2.1.1 Bulk Density

It refers to the mass ratio of a sample to the volume it occupies with a unit of kg m^{-3} for granular fertilizers. The total volume includes particle volume, inter-particle void volume, and internal pore volume. Generally, bulk density is reported in two possible ways; 1) loose bulk density or 2) tap bulk density. Loose bulk density is defined as the density obtained by pouring a fertilizer sample into a vessel of known volume without any consolidation. Tap bulk density is similar but the vessel is tapped or packed. This tapping procedure is accomplished by repeatedly dropping the vessel from a specified height at a constant drop rate until the apparent volume of the sample becomes nearly constant.

Bulk density can vary within and between different fertilizer products (Table 2.2). Ammonium nitrate (34-0-0) has a bulk density of 800-900 kg m^{-3} and ammonium sulfate (21-0-0) 700-800 kg m^{-3} (Solutions for Agriculture, 2013). Both the products provide nitrogen (N) but their bulk density values differ. Sources of phosphorous such as DAP (18-46-0) and the blend, 10-34-0 supply nitrogen but have different bulk densities; 900-1000 kg m^{-3} and 1400 kg m^{-3} (Solutions for Agriculture, 2013).

Table 2.2. Reported bulk densities for both individual fertilizer constituents and typical blends.

Product	Nutrient Concentration $N-P_2O_5-K_2O$ (%)	Bulk Density (kg m^{-3})
Ammonium nitrate	34-0-0	800-900[1]
Ammonium sulfate	21-0-0	700-800[1]
Urea	46-0-0	700-800[1]
Diammonium phosphate (DAP)	18-46-0	900-1000[1] 1040 (tapped)[2]
Muriate of Potash (KCl)	0-0-60	900-1000[1]
Triple Super Phosphate (TSP)	0-46-0	1000-1200[1]
Blend	28-0-0	1300[1]
Blend	32-0-0	1300[1]
Blend	10-34-0	1400[1]
Blend	20-20-20	700[3]
Blend	13-13-21	900[4]
Blend	15-15-15	900[4]

1) Solutions for Agriculture, 2013
2) The Mosiac Company, 2013
3) Material Safety Data Sheet, 2010
4) Tissot et al., 1999

2.2.2 Particle Properties of Granular Fertilizers

Particle properties of fertilizers vary among and between different sources of fertilizers. Mean particle size, Size Guide Number (SGN), particle density, particle hardness constitute the main physical properties of fertilizer particles. These are important to understand as they can reflect the quality of a fertilizer and ability of an applicator to spread the material. The follow defines and discusses each of these particle physical properties in more detail.

2.2.2.1 Particle Size

Particle size represents an important physical property which serves as an indicator of both quality of a fertilizer product but also the size uniformity or variability of size for a material. This variable represents the size dimension of a particle typically reported as a mean or median diameter when discussing granular fertilizers. Particles are three dimensional objects so there are different measures to express their size are discussed.

i) Median Particle Size (d_{50}) and Size Guide Number (SGN): Median particle size (d_{50}) represents the median diameter of fertilizer particles in a sample and is reported using the term d_{50}. As an example, a $d_{50} = 1.0$ mm indicates that 50% of the particles have a diameter greater than 1.0 mm with the other 50% less than this value. Mean particle size will typically vary between and among fertilizer products. Table 2.3 provides d_{50} for various fertilizers. Urea can have a d_{50} of 2.2 mm (Aphale et al., 2003) whereas ammonium sulfate is usually smaller in size having a d_{50} around 1.5 mm (Hofstee and Huisman, 1990). Both of these products are base sources for N but have significantly different median particle sizes. Potassium particles are considered to be greater in size compared to nitrogen. As an example, potassium chloride (KCl) was reported to have a d_{50} equal to 2.3 mm (Aphale et al., 2003). When looking at phosphorous sources, they are typically larger than nitrogen and potassium. Triple super phosphate can have a d_{50} around 2.7 mm (Yildirim, 2006).

Another method of reporting particle size is the Size Guide Number (SGN). SGN is defined as the mean particle size (d_{50}) multiplied by 100. As an example, if d_{50} is 2.7 mm then 2.7 mm X 100 results in a reported SGN of 270. It denotes that 50% of the particles in the sample are greater in size than the stated SGN while the rest are smaller than the SGN.

Table 2.3. Variation in median particle size of for different fertilizers and common blends.

Product	Nutrient Concentration $N-P_2O_5-K_2O$ (%)	Median Particle Size, d_{50} (mm)
Ammonium Nitrate	34-0-0	2.2[5]
Ammonium Sulfate	21-0-0	1.5[1]
Urea	46-0-0	2.2[2]
Triple Super Phosphate (TSP)	0-46-0	2.7[3]
Diammonium Phosphate (DAP)	18-46-0	3.2[5] 3.0[6]
Muriate of Potash (KCl)	0-0-60	2.3[2]
Blend	17-17-17	2.9[5]
Blend	13-13-13	2.6[4]

1) Hofstee and Huisman, 1990
2) Aphale et al., 2003
3) Yildirim, 2006
4) Smith et al., 2004
5) Virk et al., 2013
6) The Mosaic Company, 2013

ii) **Particle Size Distribution:** Granular Spread Index (GSI) and/or Uniformity Index (UI) are two measured particle size parameters which reflect the range of distribution of particle size for a fertilizer sample. These parameters are computed differently thereby providing a difference in reporting particle size distribution. GSI can also be used as a probability indicator of fertilizers to segregate during transport, handling, loading and spreading (Antille et al., 2013). GSI is calculated using the measured variables d_{50}, d_{16} and d_{84} then computed using Equation 2.1. Lower GSI values indicate less size variation within a sample whereas larger values designate a larger range in particle size.

$$GSI = \frac{d_{84-}d_{16}}{2d_{50}} X100 \qquad (2.1)$$

where, d_{84} = diameter of the mass fraction at the 84% level for a sample (mm)

d_{16} = diameter of the mass fraction at the 16% level for a sample (mm)

d_{50} = median diameter (mm)

Similar to the median particle size, GSI can vary significantly between different fertilizer products but also within individual products (Table 2.4). Virk et al. (2013) reported a GSI of 25 for ammonium nitrate (34-0-0), 17 for DAP (Di-ammonium phosphate, 18-46-0) and 29 for potassium chloride (0-0-60). Ammonium nitrate and DAP both contain nitrogen sources but DAP had a lower GSI value. Potassium chloride (KCl) had the largest GSI value illustrating a larger range of particle size distribution.

The Uniformity Index (UI) can also be used to express the relative particle size variation. UI is the ratio of larger (d_{95}) to smaller (d_{10}) granules for a specific fertilizer multiplied by 100 (equation 2.2).

$$UI = \frac{d_{95}}{d_{10}} X100 \qquad (2.2)$$

where, d_{95} = 95% of the amount of particles at or below this specific diameter (mm)

d_{10} = 10% of the amount of particles at or below this specific diameter (mm)

A UI value of 100 signifies that all particles are of the same size. Values greater than 50-60 (Ferti Technologies, 2014) indicates a better quality in terms of uniformity in particle size and results in even distribution of nutrients. However, UI values equal to 50 indicate average particle size uniformity whereas less than 50 represent poor uniformity.

Table 2.4. Variation in particle size distribution of different fertilizer sources including a blend.

Product	Granular Spread Index (GSI), Uniformity Index (UI)
Ammonium nitrate	GSI: 25[1]
Diammonium Phosphate (DAP)	GSI: 17[1] UI: 57[2]
Muriate of Potash (KCl)	GSI: 29[1] UI: 44[3]
Blend (17-17-17)	GSI: 32[1]

1) Virk et al., 2013
2) The Mosaic Company, 2013

2.2.2.2 *Particle Density*

It is defined as the particle mass ratio to its volume and expressed with a unit of kg m^{-3}. This parameter can vary between and within different fertilizers (Table 2.5). One way to look at the impact of particle density on granular fertilizers is that as particle density increases, so does the amount of product contained within an equivalent volume thereby increasing the overall bulk density. Ammonium sulfate and ammonium nitrate are typical sources of N but can vary slightly in particle density. DAP and TSP have significantly different particle densities. In general, particle density will range between 1200 and 2400 kg m^{-3} for granular fertilizers expressing that as particle density varies, so will the resulting behavior during trajectory and conveyance. The expectation would be that products with similar particle density should behave the same unless another parameter such as particle size differs.

2.2.2.3 Particle Hardness

Particle hardness is the pressure which a particle can withstand before rupturing. The tendency of fertilizer particles to be crushed or explode into powder or dust depends on particle hardness. Fertilizer particle size and cohesion determined its hardness. The particle strength decreased with increase in diameter. Fertilizer particles should be hard enough to withstand all the processes from storage, transportation and spreading. Hofstee and Huisman (1990) reported that ammonium nitrate has a hardness between 10N and 20N, whereas ammonium sulfate ranged between 45N - 65N and urea (46-0-0) around 6N (Table 2.5). Again, these values differ for various N sources.

Table 2.5. Variation in particle density and hardness for different base granular fertilizers.

Product	**Nutrient Concentration $N-P_2O_5-K_2O$ (%)**	**Particle Density (kg m^{-3})**	**Particle Hardness (N)**
Ammonium Nitrate	34-0-0	1800^2	$10\text{-}20^4$
Ammonium Sulfate	21-0-0	1640^1	$45\text{-}65^4$
Urea	46-0-0	1300^3	6.0^4
Triple Super	0-46-0	2100^1	$10\text{-}38^4$
Diammonium	18-46-0	1600^1	50.0^4
Muriate of Potash	0-0-60	1600^2	48.3^4

1) Hoffmeister et al., 1964
2) Smith et al., 2004
3) Alireza and Sheikhdavoodi, 2012
4) Hofstee and Huisman, 1990

2.2.2.4 Coefficient of Friction

Coefficient of friction is defined as the ratio of force of friction and normal force. Friction indicates the resistance to motion of an object or objects in contact with each other. This parameter depends on the surface roughness and how materials slide against each other. It can also describe the degree of interaction between two particles when discussing granular fertilizers. As an example, ammonium nitrate and urea (both N sources) have coefficients of friction that are significantly different (Table 2.6). Ammonium sulfate is another source of N with a coefficient of friction between urea and ammonium nitrate at 0.5. One would expect these granular fertilizers to behave differently when sliding or rolling along metal or other materials thereby should be considered in the design of handling, transporting and spreading equipment.

Table 2.6. Variation in coefficient of friction for different fertilizers (Hofstee and Huisman, 1990).

Product	Coefficient of Friction
Ammonium nitrate	0.7
Ammonium sulfate	0.5
Urea	0.3
Diammonium phosphate (DAP)	0.5

2.2.3 Chemical Properties of Granular Fertilizers

Fertilizers are sold on the basis of their chemical or nutrient concentration whether a macronutrient or micronutrient. As with the physical properties of a fertilizer, chemical composition varies between products. However, chemical composition does not vary within an individual product.

2.2.3.1 Nutrient Concentration (N-P_2O_5-K_2O)

Generally, inorganic fertilizers such as diammonium phosphate (18:46:0) and potash (0:0:60) contain three basic macronutrients: nitrogen, phosphorous and potassium. The first value corresponds to total nitrogen content (percentage of N), the second indicates available phosphorus (as P_2O_5; %), and the third represents water soluble potash (as K_2O; %) content (McCauley et al., 2009).

Macronutrients such as nitrogen are required by plants so many time applied before or during growth.

2.2.3.2 Soluble Salts

High concentration of soluble salts can hinder seed germination, injure plants or may terminate a crop. Plant damage may occur if a fertilizer is placed with the seed or in a band near the germinating seed in concentrated form. The extent of plant injury due to soluble salts in a fertilizer is measured as the salt index. This index is used to compare different fertilizers products for their placements via drilling with seed, banding when lower values of salt index are preferred (Oldham, 2008). Fertilizer with a high salt index can cause plant injury (McCauley et al., 2009). In general, nitrogen and potassium fertilizers have higher salt indices than phosphorous fertilizers (Table 2.7). Salt burns occur when excessive soluble salts come in contact with the germinating seeds or roots that may result from salt forming fertilizers, improperly placed fertilizers. Salts naturally attract water so thereby draw water out of roots and causing plant injury or drought like symptoms.

Table 2.7. Salt indices of various fertilizers (Oldham, 2008).

Nutrient	Material	Salt Index
Nitrogen	Ammonium sulfate	54
	Ammonium nitrate	49
	Urea	27
	Anhydrous ammonia	10
Phosphate (P_2O_5)	Diammonium phosphate (DAP)	8
	Monoammonium phosphate (MAP)	7
	Triple superphosphate	4
Potash (K_2O)	Potassium chloride	32
	Potassium sulfate	14

2.2.3.3 Solubility

Fertilizer solubility is a measure of how much amount dissolves in water and influences the nutrient availability (McCauley et al., 2009). Nearly all nitrogen, potassium and sulfur fertilizers are completely soluble in water. To obtain high crop yields, TSP (Triple Super Phosphate) should contain greater than 90% water soluble phosphorous whereas ammonium phosphate provides between 50% to 70% (Bartos et al., 1992). As phosphorous is important for early plant growth, it is recommended that banded starter fertilizers contain greater than 60% water soluble phosphorous.

2.3 Types of Granular Fertilizer Applicators

Granular fertilizers are generally applied using either spinner-disc spreaders or pneumatic applicators. Other fertilizer application equipment and methods exist but these two types of applicators make-up the majority used in the U.S. Spinner-disc spreaders tend to be more common because of their simple design, low maintenance, cost and ease of operation (Aphale et al., 2003). Spinner spreaders have a metering mechanism and implement a centrifugal action of opposing, rotating discs, with vanes attached, for broadcasting fertilizer.

Dual disc spinner spreaders, also referred to as rotary, cyclone or centrifugal spreaders. The spreader consists of 1) hopper 2) conveyor chain 3) feed gate 4) flow divider 5) spinner discs and 6) vanes (fig. 2.1). The hopper provides onboard storage of fertilizer or lime. The conveyor chain or belt drops fertilizer over a flow divider through a feed gate onto a distribution device which generally consists of two rotary discs with vanes mounted on them. The conveyor chain speed and gate height determine the mass flow of material from the hopper and thereby application rate (kg ha^{-1}) in the field.

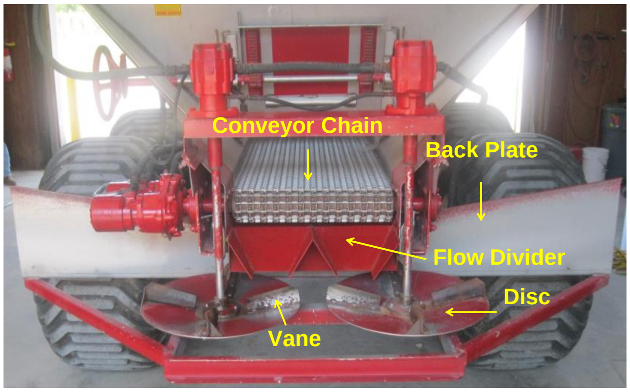


Figure 2.1. Rear view of a dual-disc spinner spreader illustrating the various hardware components used for conveying and distributing fertilizer and lime.

The function of flow divider is to split material onto the two discs. It controls the delivery point of material onto the discs. The divider can be adjusted to alter the resulting spread pattern. The back and forth adjustments of the divider impacts the resulting spread pattern. Placing the divider in the back position narrows the effective spread width whereas moving the divider forward widens and pushes material away from the centerline of the spreader.

The two spinner discs, rotating in opposite direction, generate the resulting symmetrical spread distribution pattern. The spinner discs determine the throw distance since depending on their rotational speed. The higher the disc speed, greater the effective spread width. The shape (e.g. concave) of the spinner discs also impart a vertical velocity on particles impacting their final distribution point on the ground. Different manufacturers use different types of vane designs which accelerate fertilizer particles for distribution.

Pneumatic applicators are of three types 1) 3-point hitch, 2) self-propelled or 3) trailed units. These applicators use air as the medium to transport fertilizer particles from the metering location to the point of application. The basic components of pneumatic applicators consist of a hopper, metering system, air supply, transport tubes and distribution system. A fan supplies air, of positive pressure to convey material from the metering device to the point of application. Transport tubes carry entrained material and air to the point of application. Individual distributors are spaced evenly across the boom and turn material downwards for spreading. Spread width is based on the boom length.

Figure 2.2. An example of a pneumatic fertilizer applicator during field operation. The aluminium pipes are used to convey fertilizers to deflectors along the boom for material distribution.

2.4 Evaluating Granular Spreader Performance

Spreader performance is typically described through two parameters; accuracy and spread uniformity. Accuracy and spread uniformity are key aspects for successful application of fertilizers and must be known in order to evaluate the ability to properly place nutrients. Accuracy is the intended or prescribed amount of material to apply versus the actually applied amount. Normally this is expressed in the mass applied or mass applied per unit of area. The permissible limit of variation from the target rate is 5% as outlined in a publication by Alabama Cooperative Extension System (ACES, 2009) and is achieved through proper spreader calibration. On the other hand, spread uniformity represents the quality of spread distribution over an area therefore takes into consideration the spatial aspect of the resulting pattern. Put another way, it indicates how uniform material is spread with expectations that each square area receives the same amount therefore no variability in spread would exist. The coefficient of variation (CV) is a measure used to quantify spread uniformity. Lower values of CV indicate uniform spread distribution. CV values typically vary between 5% to 10% when applying granular fertilizers with spinner spreaders (Burks et al., 2000). However, field irregularities may double this variation in spread uniformity (Parish, 1991). For actual field conditions, spread uniformity or CV will be higher and in the range between 15% to 20% (Sogaard and Kierkegaard, 1984, Fulton et al., 2005, Virk et al., 2013). In general, most consider an acceptable accuracy for fertilizer application to be within ±10% of the target rate (Davis et al., 2008) with the ag industry accepting 15% or less as acceptable.

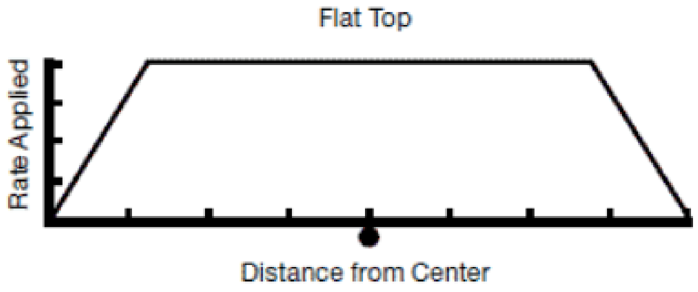
It should be noted that calibration of dual disc spinner spreaders is a required procedure to obtain satisfactory results. Calibration is especially important when changing from one fertilizer type to another or varying the feed rate of material since different setups might be required. The process of calibrating a spreader is a two-step process. The first step is to calibrate the metering of material (kg/sec) by the conveyor which results in accurately applying the target rate (kg/ha). The second step is to then ensure that material is spread uniformly behind the spreader. Spread uniformity is determined using a row of collection pans. Spreader hardware such as divider position, disc speed and/or vane mounting position are changed until an acceptable distribution is achieved. The use of poorly calibrated spreaders often results in incorrect rates causing distinct dark and light green crop patches and thereby yields variations (Scharf, 2009). Spreader calibration is important for applying the desired nutrient concentration to soils and crops and not to exceed the required nutrient limits (Marsh et al., 2003). The Alabama Cooperative Extension System (ACES) recommends that calibration and evaluation of application equipment is necessary for satisfactory field results (ACES, 2009).

2.4.1 Fertilizer Spread Patterns

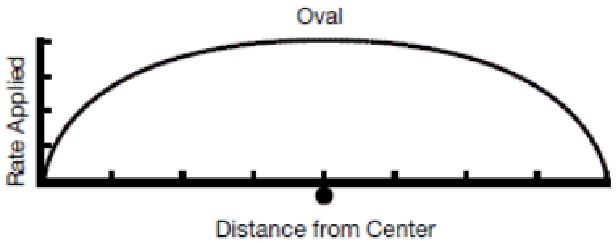
When fertilizer is applied by a spreader, the resulting distribution patterns depend mainly on the fertilizer physical properties and spreader hardware parameters. One can think of the patterns as the resulting spatial distribution generated behind the spreader and expressed in 2-D (amount applied versus transverse distance from the spreader centerline). Two types of spread patterns can be generated by spinner spreaders; a) desirable and b) undesirable. Maintaining an acceptable desirable pattern is required to reduce under- or over-application of fertilizers.

2.4.1.1 Desirable Spread Patterns

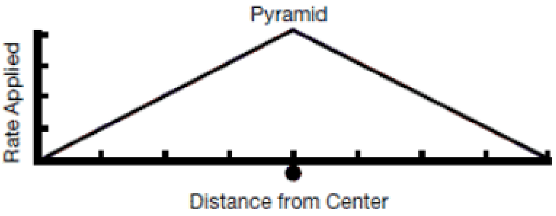
An acceptable single-pass spread pattern can be described as one which is symmetrical on either side of the centerline allowing for uniform overlapping between swaths. =Figure 2.3 presents ideal or acceptable single-pass patterns for dual-disc spinner spreaders. A flat top pattern (fig. 2.3a) has a trapezoidal shape with uniform slopes on either side. An oval or Gaussian distribution pattern (fig. 2.3b) provides 60% effective coverage (Maryland Cooperative Extension Publication, EB-254, 2002). In other words, 20% of the swath width should be overlapped in the adjacent passes to generate a uniform distribution. The pyramid pattern (fig. 2.3c) indicates that the effective swath width should be only 50% of the theoretical spread width (Maryland Cooperative Extension Publication, EB-254, 2002). Most dual-disc spinner spreaders will produce a Gaussian or pyramid single-pass pattern.



(a)



(b)

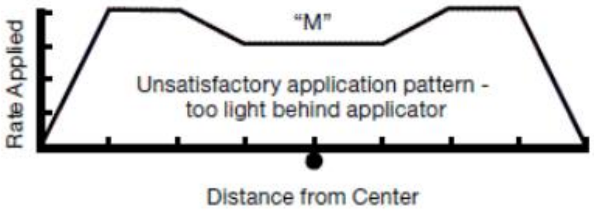


(c)

Figure 2.3. Desirable single-pass distribution patterns typical for dual-disc spinner spreaders; flat top (a), oval or Gaussian (b) and pyramid-shaped (c) (ACES, 2010).

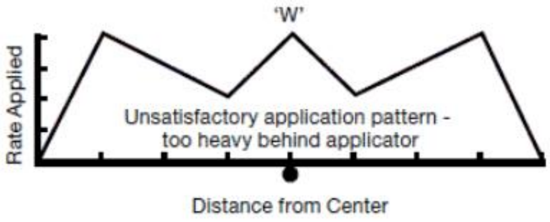
2.4.1.2 Undesirable Patterns

Examples of undesirable spread patterns are presented in figures 2.4 through 2.6. These spread patterns can occur due to a malfunctioning spreader, physical variability of a fertilizer, worn spreader hardware and driving pattern not adapted to the field shape (Maryland Cooperative Extension Publication, EB-254, 2002; ASABE Standards, 2009). Worn spreader parts such as spinner discs or vanes will negatively impact the resulting pattern. Improper adjustment of the flow divider on the spreader might result in uneven fertilizer delivery onto the discs. Field with slopes and terrain can cause heavier material application downhill skewing the resulting pattern. Fertilizer that has absorbed moisture may stick to the conveyor belt and other hardware impacting material flow and resulting distribution.



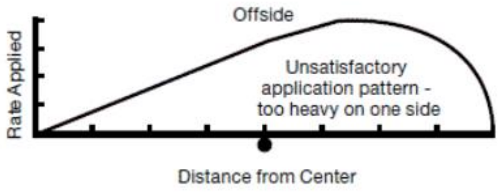
(a)

Figure 2.4. "M" shaped single-pass distribution pattern (ACES, 2010).



(b)

Figure 2.5. "W" shaped single-pass distribution pattern (ACES, 2010).



(c)

Figure 2.6. Skewed single-pass distribution pattern (ACES, 2010).

An "M" shaped distribution pattern (fig. 2.4) can occur in dual spinner disc spreaders where fertilizer is heavily placed on either side of centerline and low in the center. One possible solution would be to move the divider inwards bringing material distribution towards the centerline of the spreader. For a "W" shaped distribution pattern (fig. 2.5), areas of high material concentration are found at the pattern center and either side. This problem can be corrected by proper overlapping between the swaths and following a circular traverse during field application. A skewed spread distribution pattern (fig. 2.6) can be a common problem found for a single-disc spreader in which excessive material is accumulated on one side of the centerline. For a dual disc spreader, this pattern could occur due to material flow obstruction allowing more material to flow onto one disc. Operating on a side slope will also generate pattern skewing with heavier material applied onto the downhill side.

2.4.1.3 Simulated Overlap Spread Patterns

Single-pass patterns help establish the pattern shape from a spreader but does not represent the resulting pattern across a field since overlap is required on adjacent spinner spreader passes. Simulated overlap patterns are generated using a single-pass pattern, a given spread width and the direction of adjacent passes. In most cases, spreader operators will use a back-and-forth pattern during field application (Fig. 2.7). These three pieces of data are then used to construct the resulting overall spread pattern as depicted in figure 2.8. The overlap pattern within the effective spread width (orange dotes and line in Fig. 2.8) is then used to evaluate spread uniformity and needed spread width during field operation. This information helps establish the expected field performance of a spinner spreader and ensure the spreader is operating within the acceptable constraints (spreader uniformity 15% or less).

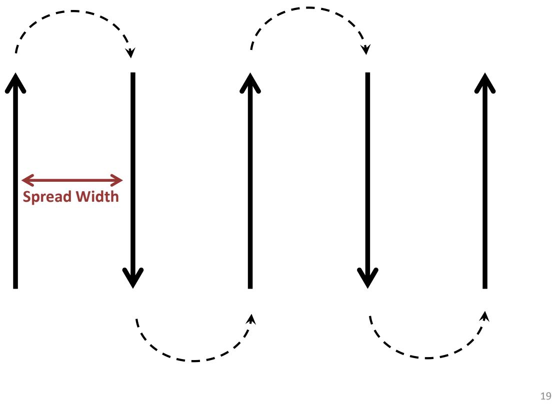


Figure 2.7. Typical field path taken by a spreader operator where back and forth passes are made. This type of path is referred to as the progressive application method.

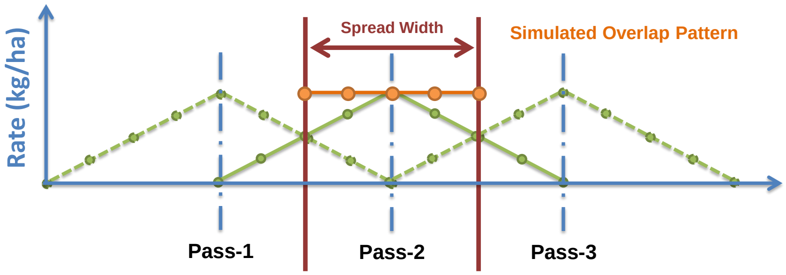


Figure 2.8. Graphical representation of using a single-pass pattern to generate the simulated overlap spread pattern indicated by the orange dots and line.

2.5 Standard Methods for Evaluating Granular Applicator Distribution

The ASABE Standard S341.3 (ASABE Standards, 2009) outlines the protocol for measuring distribution uniformity. This standard establishes a method to determine and report performance data of granular spreaders. The test requires the test site to have a slope less than 2%, wind speed lower than 8 km h^{-1} and hopper box filled 40% to 50% of its capacity. The collection pans should be approximately 30 cm in height and have compartments of 10-cm wide and 10-cm long in them, as this setup helps in minimizing material bouncing. The length of a collection pan should be equal to or greater than the pan width with a minimum of 30-cm length. The row of collection pans should exceed

10% of the anticipated effective spread width. A sufficient number of collection pans should be used during testing with a minimum of 10 pans within the effective spread width. The pans should be uniformly spaced and arranged such that they allow passage of the spreader and/or tractor. With the spreader operating in normal conditions, the top of the collection pan should not be over 10 cm above ground level. If the discharge height of spreader is less than 0.5 m, the top of the pans should not be more than 5 cm above the ground level.

ASABE Standard S341.3 (ASABE Standards, 2009) and ISO standard 5690-1 (ISO, 1985) describe using the coefficient of variation (CV) as calculated using equations 2.2, 2.3 and 2.4 to express spread uniformity. Multiple adjacent passes are used to compute the coefficient of variation (CV) for the simulated overlap patterns. Figure 2.8 provides an illustration of how single-pass data is used to create a simulated overlap pattern. There are two methods (ASABE Standards, 2009) by which an overlap pattern is generated 1) one-direction and 2) progressive. One-direction application involves successive adjacent swaths which are made in the same direction of travel (e.g. racetrack or circuitous type of application). The progressive method consists of back and forth traverses between adjacent passes during material application (Fig. 2.7).

$$X = \sum Xi/N \tag{2.2}$$

$$SD = \{\sum[(Xi - X)^2]/(N-1)\}^{1/2} \tag{2.3}$$

$$CV = \frac{SDX100}{X} \tag{2.4}$$

where, X = arithmetic mean

X_i = accumulated sample weight for each collection pan location within the effective swath width

N = number of collection pans

Effective spread width (Fig. 2.9) is determined by taking the point on the left and right side of the centerline where the application rate is half or most uniform application occurs (ASABE Standards, 2009). Another method is to use the computed Coefficient of Variation (CV) values from the simulated overlap analysis to establish the effective spread width (ASABE Standards, 2009). CV values are computed at different spread widths using the simulated overlap data. The CVs are then plotted against the different spread widths (fig. 2.10). From this plot, the effective spread width is determined from either the largest spread width associated with the minimum CV or the CV at the maximum spread width intersecting the CV=15%.

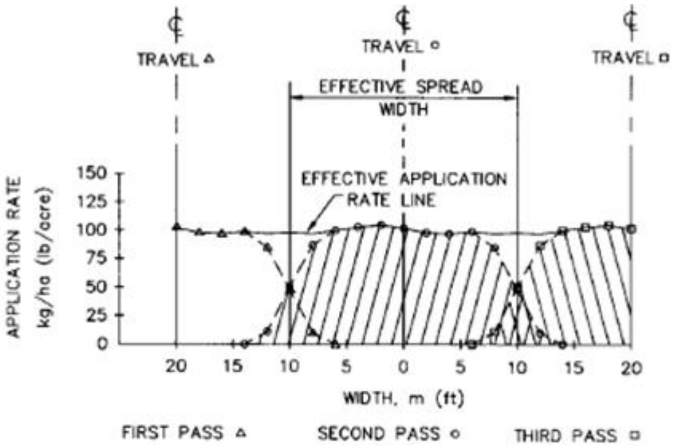


Figure 2.9. Graphical representation using a single pass pattern to generate the simulated overlap spread pattern (ASABE Standards, 2009). Effective spread width and resulting application rate line are labelled.

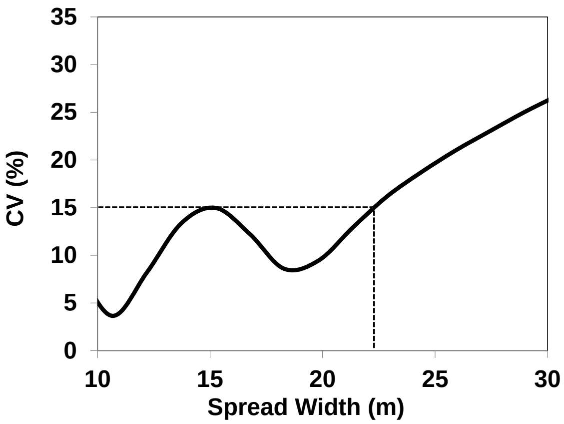


Figure 2.10. Example illustrating the typical CV (%) versus spread width curve. The point where the curve crosses the CV=15% at the maximum spread width establishes the effective spread width for a specific spreader and product.

As spinner-disc speed increases, the effective spread width also increase proportionally for a dual-disc spinner spreader. Generally, the thumb rule within the ag industry related to spinner disc spreader is that effective spread width increases by 3.0 m for every increase in spinner disc speed by 100 rpm. Theoretically, an increase in spinner disc speed would shift the CV versus effective spreader width curve to the right (Fig. 2.11 As an example, Figure 2.11 shows a 3.0 m shift in effective spread width for each 100 rpm increase in disc speed; t 18.3 m (60ft) at 600 rpm, 21.3 m (70ft) at 700 rpm and 24.4 m (80ft) at 800 rpm.

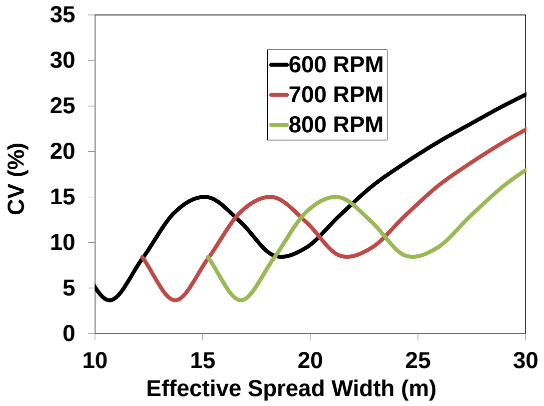


Figure 2.11. Illustration of how effective spread would change as spinner disc speed increases.

Parish (1986) evaluated spread patterns using two fertilizer materials and one spreader. He concluded that the type of material collection pans caused significant differences in optimum swath width, skewing and CV for overlap patterns. Traditional baffled pans generated CVs ranging between 8% to 20%, floor collection 21% to 41% and 27% to 57% for long narrow pans. The observed differences were due to material bouncing, impacted by the type of collection pans.

Parish (2000) compared delivery rates from collection pans and spreader calibration for three commercial spreaders and two products following ASABE Standard 341.4 (ASABE Standards, 1999) with an assumption that the delivery rate from the spreader could be erroneous. For the pattern tests, spreaders were moved three times over the pans with mass collected converted to an application rate in kg ha^{-1} using effective spread width determined in pattern test with Spreader.EZ, a computer program developed by Parish (1986). Calibration of the tractor mounted spreaders was conducted by removing the delivery system and collecting the metered material in buckets to determine the application rate. The tractor was stationary and spreader was operated for at 540 rpm for the time required to cover 465 m^2 at selected effective swath width determined in pattern test at 7.2 km h^{-1}. For the walk behind spreader, the disc was removed and laboratory test stand was used to run the spreader. The peripheral speed of the test tire was maintained at 4.8 km h^{-1} using the test stand and granular product fell into pans. The spreader was operated for the number of revolutions enough to equal 93 m^2. The significant differences were observed between half of the comparisons for the rates determined by pattern data and through calibration. The rates determined through the pattern data were higher compared to calibration data. The result occurred due to particle bouncing off the hard surface of collection pans. It was concluded that delivery rate errors can occur from pattern tests conducted on a smooth surface.

The effect of wind speed and wind direction on spread uniformity was analyzed by Smith et al. (2004), while applying different fertilizers using a spinner spreader at a disc speed of 640 rpm. Flow rates of 123, 223, and 336 kg ha^{-1} with a ground speed of 19.3 km h^{-1} and swath widths of 12, 15, and 15 m used for ammonium nitrate, potash and 13−13−13, respectively. Under cross wind applications, spread uniformity was found to be worse than into a head wind. Progressive and one-direction application patterns were found to be equally effective with respect to spread uniformity of the applied granular fertilizers. Spread uniformity (CV) increased with increasing swath width for ammonium nitrate for all wind speeds and directions. CV's of less than 15% were observed for cross winds and low wind speeds when the spread width was less than 10 m. Twelve percent of the CV's were less than 15%. For potash and ammonium nitrate, the largest and smallest CV's were associated with headwinds and tailwinds, respectively. For cross winds, 95.5%, 78.9% and 54.4 % average pan recoveries were observed for potash, 13-13-13 and ammonium nitrate, respectively. It was recommended to use the mass of material collected in pans for calibrating spinner spreaders over measuring just volume.

2.6 Fertilizer Physical Properties Impacting Fertilizer Distribution

While the intent and focus is on applying fertilizers in a uniform way, non-uniformity can occur and can be due to various reasons. In particular, variation among physical properties in fertilizers, as described in Section 2.2.1, can be a primary cause of non-uniform application. The fact that fertilizer is accelerated off the spinner discs and vanes, interactions among particles and aerodynamics will affect fertilizers with different physical properties. Therefore, the following describes how physical properties of fertilizers can influence distribution when using a dual-disc spinner spreaders.

2.6.1 Particle Size

A number of researchers conducted studies in order to determine the effect of fertilizer particle size on non-uniform application. Hoffmeister et al. (1964), Karnok (1986), Bradley and Farnish (2005), Jha and Puri (2011), Rosato et al. (2002), Bridle et al. (2004), Tang and Puri (2004), Achorn (1984) and Hardesty and Ross (1938) reported that uneven application of fertilizers occurs primarily due to differences in particle size within the product being applied. Speelman (1979) studied the influence of fertilizer particle size on spread distribution using a reciprocating spout fertilizer distributor. He recommended that particle sizes less than 1.6 mm should be removed from the fertilizer as they limit the working width due to heavy application of fines directly behind the spreader. Further, it was reported that an increase in the d_{50} of a fertilizer product also increased the spread width.

Broder and Ballay (1983) used three types of urea with different mean diameters (d_{50}) of 1.7 mm, 4.7 mm and 3.9 mm for studying the influence of particle size on spread width. It was observed that spread width increased from 10 to 20 m while using the larger particle sized urea. They found that in order to achieve optimum spread distribution patterns, adjustments to the drop point of material onto the spinner discs were necessary.

The effect of large size fertilizer particles in relation to blending of fertilizers with different particle sizes was studied by Achorn and Border (1984). They reported that preventing non-uniform fertilizer application required the average particle diameter of each compound to be within 10% of the others. Further, the distribution pattern of the blend was impacted by segregation occurring in the hopper and within the metering device and primarily a result of variation in the particle size distribution. They also indicated that ballistic segregation occurred during particle motion through the air because of variation in particle sizes within the blend.

A blend with median particle size (d_{50}) larger than 100 µm and variation of more than 30% in particle diameter could cause segregation (Williams, 1976). Kampfe et al. (1982) studied the influence of particle fines having a diameter less than 1 mm on spread distribution. The coefficient of variation (CV) increased as the percentage of fines increased.

The distance travelled by a particle increased by 100% to150% as particle size increased from 0.3 to 3.0 mm (Hollmann, 1962). When particles smaller than 1.0 mm were removed in a heterogeneous mixture of fertilizers, the spread distribution uniformity improved. Furthermore, he recommended that a limit to the spread width must exist for preventing segregation for spinner spreaders.

Jha et al. (2008) determined the distribution of fines during percolation segregation. They used angular shaped potash particles with a coarse size range of 1) 3350-4000 µm, 2) absolute fine size range of 1400-1700 µm and 3) 2000-2360 µm. In order to make binary mixtures of 2.4 and 1.7 ratios (coarse: fine) particles were mixed in 67:33, 50:50 and 33:67 proportions by weight. Then the binary mixtures were tested for bed depths of 85, 65 and 42 mm using a second generation primary segregation shear cell. It was observed that the majority of fines were concentrated on the moving walls of the shear box for both size ratios. At a bed depth of 85 mm, the segregated fines were more uniformly distributed compared to the 42 and 65-mm bed depths. The segregated fines were found to be distributed uniformly for the 33:67 mixing ratio compared to the 50:50 and 67:33 ratios. They concluded that differences in the size of particles, segregation occurred because of percolating fines through coarser particles which was termed as percolation segregation. Heymann et al. (1971) studied the impact of particle size distribution on fertilizer distribution using an aircraft. They found that for every increase of fraction particles >2.0 mm by 10%, working width increased by 1.0 m.

Segregation was studied by Hellweg and Heege (1982) as impacted by particle size of blend components. The blend was composed of two components. They determined the difference in the coefficient of variation for a blend and one of its constituents. This difference was found to increase by 8.0% for dual disc and reciprocating spout fertilizer spreaders when the differences in the d_{50} increased by up to 0.8 mm. However, for a pneumatic fertilizer spreader, no differences were observed. Therefore, it was concluded that d_{50} values for components of the blend should be matched to prevent an increase in the CV resulting in a more uneven distribution.

The influence of particle physical properties on spreading segregation of blended fertilizers was researched by Miserque et al. (2008). The study involved mixing of two identical materials (in same weight proportion 2x200 kg) that differed by one characteristic of particle size, density or shape. The fertilizer mixing was conducted with an apparatus having a vertical screw. Twenty six blends were produced and then spread in the field using a Rauch model Alpha 1142 centrifugal spreader widely used in Germany. Two types of pan arrangements were used in the study 1) 55 collection pans (50-cm square and 15-cm high) that were placed perpendicular to travel direction of the spreader, and 2) collection pans placed parallel to travel direction of spreader. It was observed that even though the spread distribution deteriorated with the blends having a GSI (Granular Spread Index) more than 30. No correlation was found between granulometric characteristics of the blend and spread distribution behavior. It was difficult to obtain lower CV with the blend mixtures having a lower GSI and median diameter less than 3 mm. Miserque et al. (2008) pointed out that the original proportion of 50/50 could become 30/70 during application in the field. Size and density were observed to cause the major differences. They also noted that fertilizer particles with the greatest d_{50} values and least GSI that the heaviest and most spherical shaped particles landed the farthest from the spreader. This research suggested that CV's lower than 15% could result in correct quantity distribution of bulk blends.

Segregation of bulk, blended fertilizers with identical physical properties except for one-size, shape or density during filling or emptying the container was studied by Miserque and Pirard (2004). While filling the container fertilizer flowed out of mixer, it formed a heap as coarse particles with higher d_{50} values concentrated on the periphery. At center of the heap, the d_{50} was observed to be less than 1.5 mm which was 10 times less compared to particles at the periphery. The difference of d_{50} of particles at the periphery of heap and center was 0.15 mm. While emptying the container, finer particles exited first over the coarser particles. The comparison between d_{50} for the first and last samples indicated a difference of 0.4 mm during emptying. Results confirmed that the GSI should be less than 15 to avoid non-uniform fertilizer application. It was also observed that chemical heterogeneity could occur due to segregation. 50/50 percent of the initial mixture by mass could result in 35/65 after the flow took place. They concluded that the absolute sum of differences between d_{16} and d_{84} must be less than 0.5 mm to avoid segregation. Non-uniformity in fertilizer application increased above this value. Chemical segregation increased with increase in difference between densities of the blend when fertilizer was in a flowing state.

The impact of particle size, shape and density on segregation in bulk blended fertilizers was investigated by Hoffmeister et al. (1964). Results indicated that non-uniformity occurred mainly due to differences in the size of fertilizer particles in blended products. Non-uniformity was studied during storage and due to ballistic action spinner disc spreaders. The larger particles landed farther down the pile during filling for storage. Shape did not generate significant segregation whereas difference in density indicated significant results. Matching the particle size distribution greatly reduced segregation. Ballistic effects induced by the spinner discs imparted an initial horizontal velocity on the fertilizer particles that tended to propel larger particles farther than smaller ones thereby resulting in segregation. Furthermore, it was recommended that storage piles in conical forms should be avoided as they promote segregation. The researchers also suggested that vibrations occurring during transportation can also cause segregation. However, Smith (1961) indicated that road travel by a spreader truck up to 50 km resulted in little segregation of material within the hopper.

A study on segregation and flowability of blended fertilizers was conducted by Jha et al. (2006). Two sizes of urea were used 3350-4000 µm (coarse) and 1700-2000 µm (fine). Flowability of the fines was studied at two equilibrium relative humidity values (ERH) of 50% and 60%. Coarse and fines were mixed in equal proportions by weight using a bench top mixer to evaluate percolation segregation. Rate of segregation for the fines at an ERH of 60% (0.024 g/s) was 117% compared to 50% ERH (0.080 g/s).

Normalized segregation rate of fine urea at 60% (0.080 g/g/ms) was 119% higher than at 50% RH (0.175 g/g/ms). It was concluded that an increase in relative humidity by 10% increased three segregation parameters; segregated fine urea mass, segregation rate and normalized segregation rate used in the study by 120%. Segregation rate and normalized segregation rate were highly influenced by equilibrium relative humidity (ERH) of the binary mixtures. This result occurred because of differential flow between the coarse (3350 – 4000 μm) and fine (1700 – 2000 μm) urea particles plus their different moisture absorbing capacities. Finally, coarse particles contained greater voids at 60% ERH compared to 50% ERH that caused greater percolation of fines through the coarse particle bed.

2.6.2 Particle Shape

Research has been conducted to determine the effect of particle shape of fertilizer granules on segregation. Hoffmeister et al. (1964), Miserque and Pirard (2004) and Miserque et al. (2008) found that shape had minimum effect on fertilizer spread uniformity. However, Pircon et al. (1964) conducted a segregation study on dry blended fertilizers and reported that particle shape contributed towards segregation because the friction factor was intimately related to particle shape. They reported that particles would move at the same speed and direction while maintaining a constant relative position to one another if two particles have the same friction factor. Tang et al. (2003) discovered that segregation was higher for a binary mixture of coarse irregular shaped particles with spherical particles compared to a mixture having both coarse and fine particles in spherical shapes. This result was caused by irregular shaped particles that could readily enter into the void spaces and secondly, voids formed by irregular shaped particles were larger compared to those formed by spherical particles.

Tang and Puri (2007) determined that particles having irregular shapes were more prone to segregation than spherical particles for binary size mixtures of glass beads and poultry mash feed. Spherical shaped mixtures were harder to mix and readily segregated due to high flowability compared to irregular shaped particles (Chaudeur et al., 2002). Segregation was found to be smaller as impacted by the particle shape compared to size ratio effect (Lawrence and Beddow, 1969; Drahun and Bridgewater, 1983). However, Tang et al. (2003) believed that size ratio and particle shape together could significantly impact segregation.

2.6.3 Particle Density

A study conducted by Maynard (2012) reported that segregation could occur even for mono-sized particles if particle density differed. The effect of varying particle density on segregation was illustrated with a binary mixture of ping pong balls and golf balls of the same size and shape. They were placed in a container and segregated when shaken which was caused by vibration. Miserque et al. (2008) reported that variation in particle density within a blend caused non-uniform distribution by a spinner spreader. Segregation was proportional to the differences in specific density of the fertilizer material since bigger, heavier and more spherical particles were projected further. Contrary, Hoffmeister et al. (1964) noted that particle density had little effect on segregation. Pircon et al. (1964) also reported the same result that specific density had little role in segregation but overall product bulk density was an important factor in minimizing segregation.

2.6.4 Particle's Coefficient of Friction

The impact of friction on discharge velocity, angle and position of fertilizer particles was studied by Patterson and Reece (1962), Cunningham (1963) and Delitz (1969). They found that as the coefficient of friction increased, discharge velocity was reduced while the duration of particles on the vane increased. It was recommended that there should be a change in the delivery point onto the discs or use of pitched vanes to compensate for the friction factor effect on spread distribution. They found that without one of these adjustments, asymmetric distribution patterns might result if fertilizer product type changed.

Delitz (1969) quantified the energy required for accelerating particles off spinner discs. With an increase coefficient of friction from 0.0 to 0.14, the amount of energy increased from 240 to 260 J/kg. An additional increase in the friction factor to 0.5 resulted in the energy decreasing to 240 J/kg. The initial energy required to overcome friction was larger than the decrease of kinetic energy. Beyond a friction factor of 0.14, the increase of friction energy was smaller than the decrease in kinetic energy. Brubach (1973) studied pitched vanes for determining particle duration on the spinner discs.

An analysis of a fertilizer spreader with tubes instead of vanes was conducted by Brinsfield and Hummel (1975). Their study established that a 10% decrease in discharge velocity occurred on increasing the coefficient of friction from 0.2 to 0.6. Galili and Shteingauz (1982) used a fertilizer spreader with a vertical disc and it was reported that the discharge velocity decreased with an increase in the friction coefficient. Pircon et al. (1964) reported that fertilizers having particles with similar friction factors produced less segregation as compared to fertilizer blends having different friction factors. This result was due to particles with higher coefficient of friction remaining longer on the spinner disc thereby reduced velocity causing segregation (Hofstee and Huisman, 1990; Coetzee and Lombard, 2011). Hofstee (1992) reported that the relative velocity of fertilizer particles increased from 1to 21 m s^{-1} with a decrease in the coefficient of friction from 20 to 10.

The effect of friction factor, restitution, shape and particle stiffness on spread distribution with the help of EDEM (Educational Discrete Element Modeling) was studied by Lidekerke et al. (2009). They found that the friction factor had the largest influence on the spread distribution and particle stiffness had the least effect. Decrease in outlet speed was observed with increase in the friction coefficient. Larger particles were observed to have greater velocity compared to smaller ones. Outlet angular speeds decreased as the particles became more spherical. Finally, they indicated that particle velocity was influenced when the friction coefficients exceeded 0.35; below this value all particles slide. Above this friction coefficient, irregular shaped particles resisted rolling whereas spherical particles did not. Rationale was that irregular shaped particles oppose each other compared to spherical particles.

2.6.5 Particle Hardness

The handling and spreading of fertilizers in relation to physical properties was studied by Hofstee (1992). He found that spread pattern and segregation of the fertilizer particles depended on breaking strength of the fertilizer. Therefore, urea was not hard enough and thereby tended have particle size reduction, sometimes to the form of powder, when impacting the spinning discs and the vanes. This resulted in small fines and powder particles being applied directly behind the spreader since unable to travel further. Forces induced on particles during spreading, storage, vibrations and air flowing, alter a blend’s uniformity and variation in the chemical properties can cause segregation as well (Marynard, 2012).

2.7 Spreader Hardware Parameters Effecting Spread Distribution

Beyond granular fertilizer physical properties, there are various parameters which impact spread uniformity most importantly spreader hardware and their adjustment or setup. Olieslagers et al. (1996) calculated fertilizer distribution patterns from a spinning disc spreader by means of a simulation model. It was established that in order to maintain constant working width and spread pattern during variable-rate application, continuous change of orifice position and angular velocity of disc was required. For variable-rate application (VRA), it was found that variation in flow rate led to fluctuations in spread patterns resulting in large deviations from the target rate. Spread width increased with increase in angular velocity of the disc. With increase in orifice diameter, the peak of center part of spread distribution pattern increased. Further, the orifice shape had a significant impact on the resulting spread distribution pattern. Segment orifice generated nearly trapezoidal distribution whereas an ellipse shaped orifice produced a “W-pattern”.

The effect of cone angle and disc speed on fertilizer distribution uniformity for a single disc-rotary spreaders was studied by Yildirim (2006). Flat and cone-shaped discs were used in this study. Cone shaped discs threw fertilizer a further distance since generating a vertical velocity component. The computed coefficient of variation (CV) ranged between 9% to 43%. The best distribution uniformity was obtained with a combination of a disc cone angle of 0° and disc revolution speed of 810 rpm and orifice diameter of 30 mm. Distribution uniformity worsened with an increase in cone angle from 0° to 10° and then to 20°. For cone angles of 0° and 10° at a disc speed of 540 rpm, the CV was less than 20% with exception for a cone angle of 10° and 50 mm orifice diameter. Increasing the disc speed (405, 540 and 810 min^{-1}) improved the spread distribution at all orifice diameters of 30, 40 and 50 mm. The study concluded that disc angle should be less than 10° at a disc speed of 540 rpm to obtain acceptable spread uniformity.

An increase in spinner disc speed increases the spread width for a dual-disc spinner spreader (Olieslagers et al.,1996). Aphale et al. (2003) reported that with an increase in spinner disc speed from 540 to 810 rpm, spread width increased. Carman (1991) found that distribution uniformity improved with increase in disc speed along with an increment of 2^0 in concave disc angle.

Adjustment in the drop point will alter the resulting spread pattern (Parish and Chaney, 1986). Rotating the drop point of material onto a rotary spreader disc tended to shift the pattern from side to side and help overcome skewing problems. However, this method of adjusting the drop point was not always adequate to correct all pattern problems. Adjusting the drop point was only effective for compensating material or operational variables in an optimal pattern. Glover and Baird (1970) stated that most spreaders must be adjusted each time the rate or material is changed to achieve an acceptable spread pattern.

Broder (1983) studied different rotary spreaders and concluded that most of the spread distribution uniformity issues could be rectified by adjusting the material drop point onto the spinner discs. Past research has found that physical and chemical properties of fertilizers, spreader design factors such as disc shape and disc angle (Hofstee et al., 1999; Grift et al., 2006), and divider design, divider position and disc speed (Aphale et al., 2003; Dintwa et al., 2004) also impacted spread distribution. In other studies, it was reported that an increase in flow rate can also deteriorate the distribution uniformity (Glover and Baird, 1973; Olieslagers et al., 1996; Parish, 2002; Yildirim and Kara, 2003 and Yildirim, 2006).

Research has been conducted on spread uniformity as impacted by vane design. Yildirim (2008) applied triple superphosphate and calcium ammonium nitrate with a single disc rotary spreader using straight, composite, forward-curved-5, forward-curved-10, back-curved-5 and back-curved-10 vane designs. Results were reported in terms of coefficient of variation (CV) with the least values indicating uniform distribution. The most uniform distribution was achieved using the forward-curved-5 vane design (CV = 9% for TSP and CV = 10% for CAN). The straight vane shape generated the worst distribution uniformity (CV = 16% for TSP and CV = 17% for CAN). Parish and Chaney, (1985) used three different commercially available walk behind rotary spreaders, the first used two curved and two straight vanes, the second with four straight vanes and the third one was equipped with four straight vanes on its discs; the authors found that the spreader with a helical cone for drop point control resulted in better distribution patterns.

Other studies reported that vane profile and vane position on the disc influenced material flow, thereby affecting the spread pattern (Yildirim and Kara, 2003; Yildirim, 2006; Yildirim, 2008; Yildirim and Kara, 2012). Yildirim and Kara (2003) conducted a study with five different vane heights of 25, 35, 45, 55 and 65-mm mounted on a 500-mm diameter flat disc applying triple superphosphate and calcium ammonium nitrate with orifice diameters of 30, 35, 40 and 45-mm. They found that uniform distribution could be obtained with a vane height of 35-mm (CV = 7%) and 35-mm orifice diameter while using TSP with rotary fertilizer spreaders at varying flow rates. The CVs ranged from 8% to 20% for the remaining vane heights with different combinations of orifice diameters. While using CAN, vane heights of 35 and 45 mm resulted in CVs of 6% using a 35-mm orifice diameter while the remaining vanes generated CVs between 7% and 17%. Vane number also impacted spread distribution for a single disc rotary spreader (Yildirim, 2006). Results indicated that the most uniform distribution was obtained using a combination of 2 vanes versus 2, 4, 6, 8, 10 or 12 and circular orifices with diameters of 30, 40 and 50 mm. Further, spread uniformity deteriorated (CVs increased) as vane number increased.

Apart from the above cited parameters, irregularities in field surfaces and slope along with the amount of fertilizer being applied impact fertilizer particle flow behavior for a spinner spreader. Furthermore, wind speed and direction also influence particle trajectories off the vane/disc assembly (Smith et al., 2004). Tissot et al. (2002) reported that spread uniformity was also linked to the operator’s skills. Furthermore Fulton et al. (2003) reported that an incorrect offset distance between a GPS antenna and point of application can cause errors along with GPS latency when using variable-rate technology (VRT).

2.8 Impact of Non-Uniform Fertilizer Application on Crop Yield

Uneven application of fertilizers can reduce net returns plus generate uneven crop growth with varying dates of maturity (Reed and Wacker, 1970). Also over-application of fertilizers may negatively impact the environment. Today, it is important to utilize fertilizers in an efficient manner while ensuring sufficient soil nutrition for maximum profitable yields.

Jensen and Pesek (1962a) estimated the yield losses for corn in Iowa with different initial soil fertility levels and N applied non-uniformly. They found corn yield losses of 744, 268 and 37.5 kg ha^{-1} for very low, low and medium fertile soils respectively. Nutrient segregation alone has been found to cause yield loss of 312 kg ha^{-1} (Jensen and Pesek, 1962b). However, Wells et al. (1992) reported that non-uniform fertilizer distribution did not affect corn yield. Randall and Hoeft (1988) found that yield response in fertilized corn was only 10% greater than totally un-fertilized soils and was considered very small. Welch et al. (1964) studied the impact of uniform and non-uniform fertilizer distribution on corn yield. They indicated that yield decreased with the magnitude of non-uniformity.

2.9 Discrete Element Modeling (DEM)

A major factor that contributes towards cost of production is the processing and handling of particulate material in many industries. In order to reduce these costs, new design of machinery and handling techniques can help improve efficiency. Discrete Element Modeling (DEM) is a tool for modeling particle flow and processes. DEM is a combination of particle inertial properties (e.g. size, shape, density) and mechanical properties (stiffness, elasticity, plasticity) along with interaction between particles and other objects; particle or boundary surfaces (Curry, 2012).

Liedekerke (2009) reported that DEM was considered to reduce experimental calibration. Liedekerke et al. (2008) found DEM was key to increase the understanding of the spreading process, the design of better spreaders and reduction of experimental calibration. Development and validation of DEM-models can be used to optimize spreader design. Recent developments of the DEMeter++ software have made it possible to run simulations with 10^7 particles on parallel architectures, opening the way to use of more realistic models for the physics and geometry of particles within DEM simulations.

The effect of friction factor, restitution, shape and particle stiffness on spread distribution was studied by Lidekerke et al. (2009), using of EDEM modeling. They found that friction factor had the largest influence on the spread pattern distribution and particle stiffness had the least effect. They modeled particle flow through DEM simulations in order to find an alternate for the evaluation of the centrifugal spreaders in large halls which involve huge costs. Zhou and Ooi (2009) used DEM to investigate the base pressure distribution underneath a granular pile using spherical and non-spherical particles. The spherical assembly appeared to produce a more erratic pressure profile with a less significant pressure drop than the non-spherical particles. The results were in good agreement with other published experimental observations.

Coetzee (2011) developed a DEM model of a centrifugal fertilizer spreader. A single set of spreader settings was used to experimentally measure the resulting spread pattern. A sensitivity analysis was then performed to determine the most accurate set of DEM parameters for predicting the spread pattern. The particle-wall friction coefficient, the particle–particle friction coefficient, the particle stiffness and the contact damping ratio were individually changed with the resulting spread pattern compared to the reference pattern. It was found that the model was not sensitive to particle stiffness or contact damping. Particle-wall friction influenced the results the most, followed by the particle–particle friction coefficient. With an increase in the friction coefficients, particles remained on the disc longer causing the spread pattern to rotate in the same direction as the disc. The spread pattern was determined experimentally for different spreader settings. The effect of disc speed, feed rate, feed position and vane angle was investigated. It was shown that with an increase in disc speed, the spread pattern moved further away from the disc or centerline of the spreader. Also, with an increase in disc speed, particles left the disc earlier so that the pattern rotated in the opposite direction of disc rotation. With an increase in feed rate, the spread pattern widened as more particles left the disc later. Vane angle was moved backwards resulting in the spread pattern moving in the direction opposite of disc rotation. The DEM model could accurately predict all these trends and in most cases good quantitative correlations with the experimental results were found. It was concluded that DEM was a valuable tool in the development, testing and calibration of centrifugal fertilizer spreaders.

2.10 Proposed Methods of Reducing Segregation

Yule (1996) suggested that material stability, correct storage and transportation are important in maintaining material integrity which might help in reducing segregation. However, Pircon et al. (1964) suggested that for blended fertilizers where each material is present in a range of particle sizes, segregation cannot be avoided completely, but it can be minimized through proper choice of particle size range of the different ingredients. They found that compaction could be one way to reduce segregation. Hoffmeister et al. (1964), Miserque and Pirard (2004), Hofstee and Huisman (1990), Hart (1998), Achorn (1984) and Hardesty and Ross (1938) found that a blended fertilizer should be produced using similar particle size with 10% or less variation in size to minimize segregation. Hoffmeister (1964) indicated that if materials are handled in a way that causes particle size segregation in a storage pile or bin, uneven fertilizer distribution might result. Harnby (1973) proposed that segregation can be reduced by using liquid fertilizers as they pose less chances of segregation. He also found that spinner spreaders with a mechanical screw or conveyor feeding unit could be placed in the hopper to avoid segregation within the fertilizer load due to settling of fines at the bottom and coarse ones on the periphery of the heap.

A very important consideration is to minimize the particle size distribution or GSI within a blend or individual product. A low GSI would indicate particle size would be more consistent making it more consistent to spread. Segregation can be avoided if the GSI which is a measure of particle size variability is lower than 15 Miserque and Pirard (2004). GSI values higher than 25 are characterized by excessive size segregation of particles. The mixture of the blended fertilizers must have Granular Spread Index of about 10 to present no risk of segregation (Miserque and Pirard, 2004). Chemical heterogeneity is also caused by granulometric segregation. Materials should be selected in such a manner that they should not chemically react in the blend (Formisani, 2005).

2.11 Summary

Fertilizers are vital to crop production worldwide but also represent a finite resource that can be an environmental risk through improper management. Spinner disc spreaders are used extensively in the U.S. to apply fertilizers. At the farm level, uniform application of fertilizers is important to ensure maximum profit while maintaining environmental stewardship. Spread accuracy and uniformity is mainly influenced by the design of application equipment and fertilizer physical characteristics. Differences in fertilizer physical properties such as size, shape, density, friction and breaking strength can influence distribution using spinner disc spreaders. Spreader hardware such as vane shape, spinner disc design and divider position also impacts the quality of fertilizer distribution. Besides distribution, fertilizer segregation can occur if variation in particle size is not within 10% and GSI greater than 15. With the growing interest in precision-agriculture (PA) technologies that allow farming equipment to traverse over the same path year-after-year, non-uniform distribution may accumulate and ultimately lead to unbalanced soil fertility levels. However, a number of factors exist which impact spread patterns. Use of VRT and appropriate hardware design (e.g. disc design and vane) can help in decreasing non-uniformity of distribution for spinner spreaders.

Chapter 3 VANE DESIGN IMPACT ON FERTILIZER DISTRIBUTION FOR A DUAL-DISC SPINNER SPREADER

3.1 Abstract

Spinner-disc spreaders are used extensively for application of granular fertilizers with components (divider, spinner-discs, and vanes) influencing material flow behavior and distribution. Fertilizer ricocheting off these components is an uncontrolled aspect of material behavior that negatively impacts spread distribution. Therefore, an investigation was conducted to understand the impact of vane design on fertilizer flow and ricocheting for a dual disc spreader. Stationary tests using a collection device to capture fertilizer particles exiting the vanes and standard pan testing were conducted to evaluate material distribution using four different vane designs. Vanes included one common to this spreader with a forward tapered top edge at an angle of 32°(Vane-1), the same design but the top edge tapered backwards at 15° (Vane-2), a U-channel but tapered style (Vane-3) and a U-channel design with constant height (Vane-4). The level of ricocheting was significantly impacted by top edge design of vane. The forward upward facing top edge of the Vane 1 generated the maximum ricocheting of 26% when the particles contacted it. However, the rearward facing top edge of the Vane 2 resulted in backward rotation on the particles contacting it thereby reducing ricocheting in half (13%). The majority of ricocheting occurred when particles contacted the vanes compared to the discs. The level of ricocheting increased with spinner-disc speed. Ricocheting generated an uncontrollable aspect of the spread pattern with these particles applied along the

centerline of the spreader. The effective spread width increased with disc speed. All four vane designs generated equal effective spread widths of 18.3 and 21.3-m at 600 and 700 rpm respectively. However, at 800 rpm, Vane 4 generated the greatest effective spread width of 24.4-m compared to 22.9- m for the other three vanes. The difference at 800 rpm was due to the enclosed rectangular, U cross-section of Vane 4 which increased the horizontal velocity vector upon exit. Finally, spread uniformity varied by vane design with Vane 2 consistently generating the lowest and most consistent CVs across all spinner disc speeds.

3.2 Introduction

Fertilizers are required for efficient and profitable crop production worldwide. Efficient use of fertilizers will be more critical in the future as increased crop yields are warranted to meet global food demand for the growing population (FAO, 2012). Further, sound nutrient stewardship must be followed at the farm level to minimize environmental risks and generate sustainable production practices. According to USDA (2010), the US ranked second with 14.9% of the world's total fertilizer consumption with an annual uptake of 21 million tons. Between 2002 and 2012, ammonium nitrate prices increased by 62%, super phosphate by 67% and potassium chloride by 75% respectively (ERS-USDA, 2012). Spinner-disc spreaders are extensively used in the United States for applying fertilizers since able to apply various granular fertilizers, easy to maintain, have large swath widths (21.3-m to 30.5-m) and simple to operate (Aphale et al., 2003). These types of applicators discharge fertilizer from a hopper using a conveyor chain or belt and then broadcast fertilizer or lime via two discs with vanes rotating in opposite directions. Escalating fertilizer prices along with requirements to minimize over-application requires improvements in the performance of spinner spreaders by ensuring accurate and uniform distribution. Fertilizer over-application causes economic loss and environmental implications while under-application leads to reduced yield (Sogaard and Kierkegaard, 1994). The fertilizer industry has developed the 4R's to nutrient stewardship (Right Rate, Right Source, Right Time and Right Place). Focus which emphasis accurate placement of nutrients as a means to enhance nutrient application and use-efficiency.

Various parameters exist that impact material distribution with spinner-disc spreaders. Broder (1983) studied different rotary spreaders and concluded that most of the spread distribution uniformity issues could be rectified by adjusting the material drop point onto the spinner discs. Past research has found that physical and chemical properties of fertilizers, spreader design factors such as disc shape and disc angle (Hofstee et al., 1999; Grift et al., 2006), divider design, divider position and disc speed (Aphale et al., 2003; Dintwa et al., 2004) also impact material distribution. An increase in flow rate can also deteriorate spread uniformity (Glover and Baird, 1973; Olieslagers et al., 1996; Parish, 2002).

Research has been conducted on spread uniformity as impacted by vane design. Yildirim (2008) applied triple superphosphate and calcium ammonium nitrate with a single disc rotary spreader using straight, composite, forward-curved-5, forward-curved-10, back-curved-5 and back-curved-10 vane designs. Results were reported in terms of coefficient of variation (CV) with the least values indicating uniform distribution. The most uniform distribution was achieved using the forward-curved-5 vane design (CV = 9% for TSP and CV = 10% for CAN). The straight vane design generated the worst distribution uniformity (CV = 16% for TSP and CV = 17% for CAN). Parish and Chaney

(1985) used three different commercially available walk behind rotary spreaders, the first used two curved and two straight vanes, the second with four straight vanes and the third one was equipped with four straight vanes on its discs; the authors found that the spreader with a helical cone for drop point control resulted in better distribution patterns. Various other studies reported that vane profile and vane position on the disc influenced material flow, thereby affecting the resulting spread pattern (Yildirim and Kara, 2003; Yildirim, 2006; Yildirim, 2008; Yildirim and Kara, 2012). Yildirim and Kara (2003) conducted a study with five different vane heights of 25, 35, 45, 55 and 65-mm mounted on a 500-mm diameter flat disc applying triple superphosphate (TSP) and calcium ammonium nitrate (CAN) with orifice diameters of 30, 35, 40 and 45-mm. They found that uniform distribution could be obtained with a vane height of 35-mm (CV = 7%) and 35-mm orifice diameter while using TSP with rotary fertilizer spreaders over varying flow rates. CVs ranged from 8% to 20% for the remaining vane heights with different combinations of orifice diameters. While using CAN, vane heights of 35 and 45 mm resulted in CVs of 6% with a 35-mm orifice diameter while other combinations of vane height and orifice diameter had between 7% and 17%. Vane number also impacted spread distribution for a single disc rotary spreader (Yildirim, 2006). Results indicated that the most uniform distribution was obtained using 2 vanes versus 4, 6, 8, 10 or 12. Spread uniformity deteriorated (CVs increased) as vane number increased.

3.3 Sub-Objectives

Among the spreader hardware parameters that impact distribution uniformity, vane design is considered important as it controls effective spread width and spread quality. Therefore, this study focused on improving spread uniformity of dual-disc fertilizer spreaders. Specific objectives were to 1) evaluate the influence of vane design on particle ricocheting off the vanes and discs, 2) determine the impact of vane design on distribution including spread uniformity and effective spread width 3) understand particle flow interaction on the vane-disc assembly.

3.4 Material and Methods

A commercially available spinner-disc spreader (fig. 3.1; Chandler Equipment Company, Gainesville, GA USA) was used in this study. The spreader was equipped with hydraulically controlled rear spinner-discs and a stainless steel mesh conveyor chain. Four equally vanes were mounted on each spinner disc. The spinner discs were concave in shape with 0.60 m in diameter, 0.04-m height and nominal 9.3º exit angle at the tip. Hydraulic power for the conveyor chain and spinner discs was maintained using proportional valves (Brand Hydraulics, Omaha, NE) with pulse width modulation (PWM) regulation. A John Deere 7230 tractor was used to pull the spreader and was equipped with a Raven SmartTrax guidance system using RTK correction and an Envizio Pro (Raven Industries, Part No. 0633001002 Revision-B S.No. 1450). The Envizio Pro and associated rate controller provided conveyor and spinner disc speed management based on user input parameters. The rear divider used to split material flow and control delivery location onto each disc was modified so no back plate or other obstruction was present during tests. The intent was to evaluate material behavior as it flowed onto the spinner discs and across the vanes. Therefore, an open divider towards the rear of the spreader was required.

The spreader and rate controller were calibrated prior to testing, following the manufacturer's recommendations as outlined within the operator manuals. Final hardware set-up for the spreader was a gate height of 0.08 m and divider position of 4 which was maintained for all the tests. The conveyor flow rate was calibrated to within 2% of the target rate programmed into the Envizio Pro.

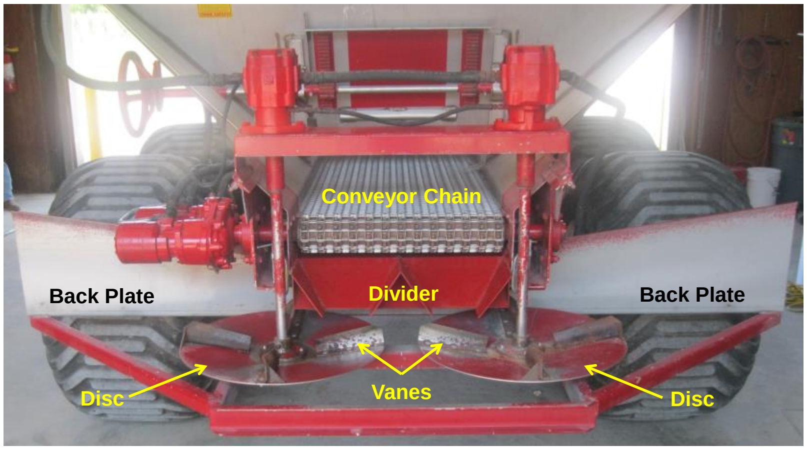
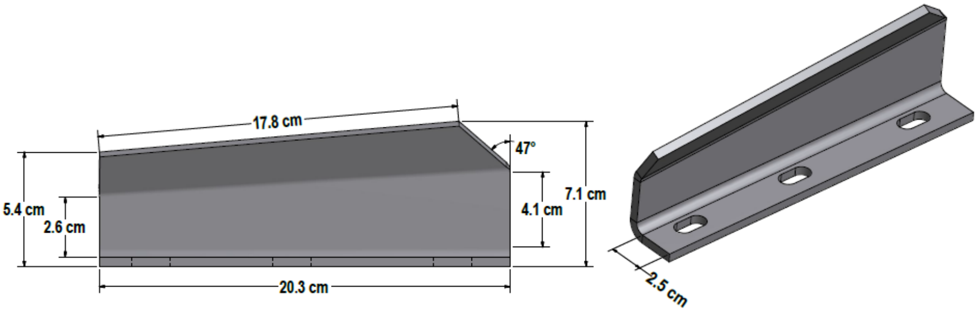
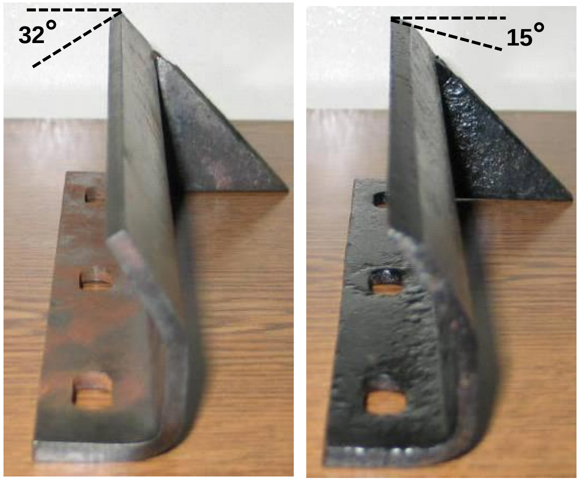


Figure 3.1. Rear view image of the spreader showing arrangement of vanes on spinner discs and different hardware components.

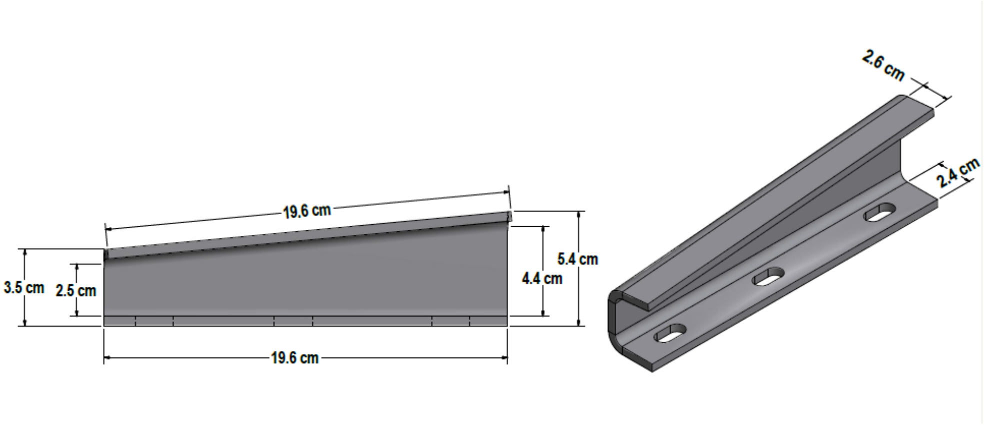
Four types of vanes fabricated from 6.35 mm steel (fig. 3.2), control treatment-Vane 1 (fig. 3.2a), control treatment vane with the top tapered backwards-Vane 2 (fig. 3.2a), tapered channel vane-Vane 3 (fig. 3.2c) and channel design-Vane 4 (fig. 3.2d) were tested. The top edge of vane 1 was forward faced at an angle of 32° whereas Vane 2 featured tapering of 15° facing backwards. Figure 3.2b represents the actual physical difference between the top edges of the vanes 1 and 2. The vanes 1, 2 and 3 had varying height from inside out and increased contact area to the particles thus making them more open faced at the exit ends. However, the Vane 4 had constant height and contact area to the particles contacting it.



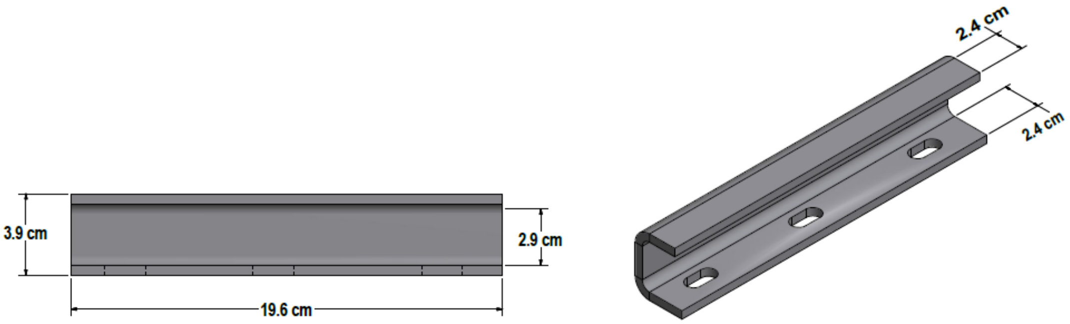
(a) Common geometrical dimensions of Vanes 1 and 2.



(b) Differences in the top edges of Vanes 1 and 2.



(c) Vane 3.



(d) Vane 4.

Figure 3.2. Front and Isometric views along with geometric dimensions for the four different vane designs. Additional views provided to highlight differences between vane designs.

3.4.1 Experimental Design

Two types of experiments were conducted at EV Smith Research Center, Shorter, AL using potash (0-0-60) as the test material. Stationary tests comprised of positioning the spreader in a static location and mounting a collection device (fig. 3.3) to quantify the particle exit points off the vanes and ricocheting behavior. Standard pan testing was conducted following ASABE Standard S341.3 (ASABE Standards, 2009) for estimating spread distribution patterns, uniformity and effective spread width as impacted by the vane designs. The two feed rates (224 and 448 kg ha^{-1}) and three spinner disc speeds (600, 700 and 800 rpm) were established as treatments. These treatments provided evaluation of each vane design over common application rates and range of disc speeds. All the tests were replicated 3 times at each rate comprising 18 tests for one vane design and an aggregate of 144 experiments for all four vanes and both types of tests.

3.4.2 Stationary Testing

A collection device with five partitions was mounted behind the spreader (fig. 3.3) to capture potash accelerated off the vanes. Each partition was labeled and called a zone between 2 and 6. The collection device was positioned so the bottom of each zone was just below the disc edge while its height covered the entire height of vanes. This positioning ensured only particles accelerated by a vane were captured within zones 2 through 6 and were considered the preferred or desired zones to capture potash. Zone 1 (fig. 3.3) was put directly underneath the two spinning discs. The zone 7 represented potash particles not captured by the collection device. Preliminary testing indicated that zone 7 was comprised of fertilizer particles bouncing or ricocheting off the vane-disc assembly with little material contacting the back plate and falling to the floor. Zones 1 and 7 represented undesirable areas for potash to land or to be captured. These two zones (1 and 7) represented an uncontrolled aspect of potash distribution which needs to be minimized. Plastic containers were used to collect material captured in Zone 1 through 6 (fig. 3.4). The material was then weighed using a digital scale and recorded to nearest 0.5 kg. The amount of potash captured in Zone 7 was computed by taking the total mass discharged by the spreader as recorded by the Envizio Pro controller and subtracting the total mass collected in Zones 1 through 6. Table 3.1 provides a more detailed description of each of the seven zones.

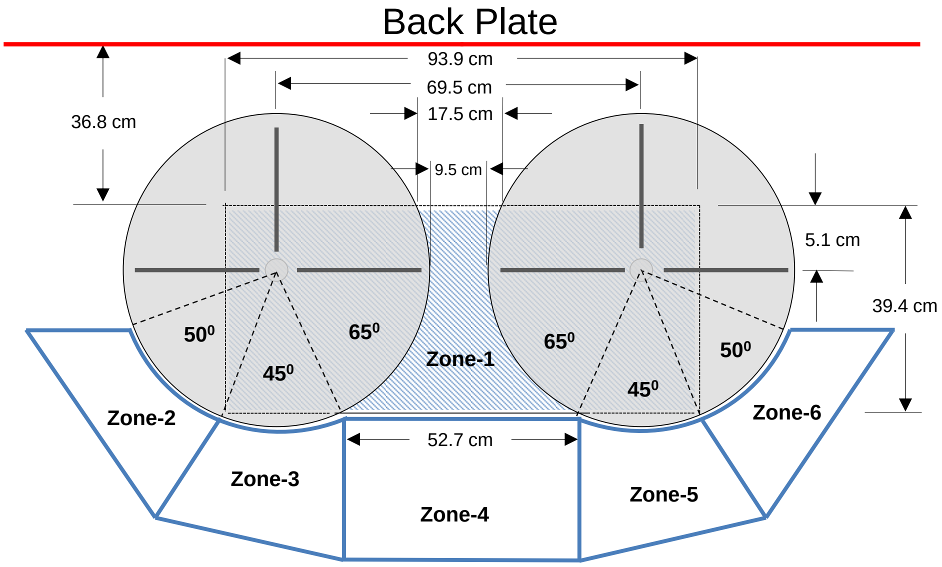


Figure 3.3. Top view of spinner discs and collection device (showing zones 2 through 6) used to evaluate exit location of fertilizer particles from discs and vanes. The figure also illustrates zone divisions and their location relative to the disc and back plate. Zone 1 (shaded region) collected material below and between the spinner discs.

Figure 3.4. Illustration of the fabricated collection device mounted on the spreader and containers used to accrue material by zone.

Table 3.1. Description of Zones 1 through 7.

Zone No.	Type of Zone	Zone Definition and Description
1	Uncontrolled	Represents fertilizer particles collected by two possible ways between the two spinner discs; 1) those which did not contact the vanes or discs thereby falling directly between the discs, or 2) others which through contact interactions with other particles fell into this area. Fertilizer captured represented contribution towards the center peak of the spread pattern.
2 & 6	Controlled	Represented a non-interaction area where particles departed the vane in a controlled manner. The end point of this zone was defined by a tangent line which intersected the end of back plate and the disc on the same side. The result of defining this end point would ensure particles exited the vanes without contacting the rear plate.
3 & 5	Controlled	A non-interaction zone and one from which fertilizer particles exited the vanes in a controlled manner. Represented at 45º angle on each disc.
4	Controlled / Interaction	A zone defined mainly as an interaction area of particles accelerated by both spinner discs. These particles were coming directly off the vanes but in an area where particle interaction exiting both discs was high. However, these particles had sufficient velocity to be trajected and land around the centerline of the spreader thereby contributing to the center peak of the distribution pattern.
7	Uncontrolled	This zone represented material that ricocheted off the vanes and discs. Fertilizer particles landing in this zone was characterized as an uncontrolled distribution.

3.4.3 Standard Pan Testing

Single pass pan testing was conducted with the spreader moving at ground speed of 12.9 km h^{-1}. ASABE Standard S341.3 (ASABE Standards, 2009) was followed to quantify distribution patterns by vane design over different rate and disc-speed treatments. Collection pans measuring 50.8 cm long x 40.6 cm wide x 10.2 cm tall were used to collect applied material. A 10.2 cm x 10.2-cm and 5.1 cm tall grid was placed in each pan to minimize material loss. A single-row of 49 pans was used which were uniformly spaced 0.8 m apart. The pans on either side of center pan were removed to allow tractor and spreader pass unobstructed. All the experiments were conducted in a level field (slope < 2%), with hopper filled up to 40-50% capacity and on the days when sustained wind speed was less than 8 km h^{-1} (ASABE Standards, 2009). The material collected in each pan was placed in containers labeled accordingly to transverse location and treatment. Samples were then weighed using a scale (Adventure Pro, OHAUS) measuring to the nearest 0.01 gm. Mass (g) of the material captured in each pan was converted to an application rate (kg ha^{-1}) through division of the pan area (2065 cm^{-2}).

3.4.4 Physical Properties

An *in situ* bulk density instrument (Berckes Manufacturing, Canby, MN USA) was used to estimate the bulk density of potash during tests. Bulk samples were collected at random from hopper of the spreader during stationary and field tests to determine particle size and particle density of potash, which were collected in the plastic labeled bags and sealed afterwards. Camsizer (Model 216753, Retsch Technology GmbH, Germany) was used to determine the particle size distribution. Five hundred grams of the bulk samples were used to determine particle size distributions. The Granular Spread Index (GSI); equation 2.1 was computed to quantify particle size variability. Particle density of the bulk samples was determined using a gas displacement pycnometer (AccuPyc 1130, Micromeritics Instrument Corp. Norcoss, GA).

3.4.5 Investigating Particle Behavior

High speed video was utilized to understand how fertilizer particles interacted as they flowed off the conveyor, across the divider, and onto the spinner discs. These videos also provided an evaluation means to observe how fertilizer interacted with the vanes and spinner discs plus visualizing the exit point of particles. The spreader was parked in a stationary location to collect this video information. The videos were captured at 480 frames per second using high definition video camera (Model No. NEX-FS700U. Sony Corp. of America, New York, NY USA). Videos were brought back to the lab then analyzed individually to observe how potash particles contacted the vane surface plus evaluate flow behavior on discs and vanes for all four vane designs.

A discrete element modeling (DEM) software called EDEM® by DEM Solutions Ltd. (Edinburgh, UK) was used to understand particle behavior including ricocheting and resulting distribution patterns. This simulation package consists of three main components; Creator, Simulator and Analyst. The Creator function enables the loading of CAD (Computer Aided Design) models, characterization of the bulk material or particles, and selection of the physics to model the spreader and fertilizer materials. The Simulator provides the actual simulation capabilities which includes the tracking of individual particles, contact between objects, and calculates this resulting particle behavior. The Analyst feature enables playback of a simulation along with visualization of resulting physical behavior such as particle vectors and summary analysis. Due to constraints on EDEM setup, only Vane 1 was used within this simulation software to directly evaluate and understand the controlled versus uncontrolled aspect of fertilizer flow and distribution. A simplified but correctly scaled CAD model was developed to represent the hopper, conveyor chain, divider, disc and vanes. This CAD representation was uploaded into the Creator function. Fertilizer particles were modeled as spherical with 6-mm diameter. Simulations were run with particles isolated between ricocheting and those distributed by vanes. All particles were tracked with final landing location on the defined ground noted with single pass patterns for the controlled and uncontrolled aspects of particle distribution generated. The divider location was changed to determine how these two patterns were altered. Single-pass patterns were plotted and compared.

3.4.6 Data Analysis

For determining the particle exit behavior impacted by the vane design within a specific disc speed, material concentrated in Zones 1 through 7 were calculated and statistically analyzed using Analysis of Variance (ANOVA) at a 95% confidence level within Minitab (v16). For determining the controlled material flow behavior, Zones 1 and 7 were excluded and percentage material concentrations re-calculated for Zone 2 through 6. Multiple comparisons were conducted using Tukey Kramer procedure to analyze the vane design impact on particle exit behavior off it with the increase in spinner disc speed and within a specific speed.

Single-pass spread patterns were generated for each treatment by taking the mean mass of material caught at each transverse position. This data was then used to create the simulated overlap pass patterns using the progressive method (ASABE Standards, 2009). These overlap patterns allowed for the mean application rate, standard deviations and coefficient of variations (CVs) to be calculated for all vane designs in order to evaluate spread uniformity.

In order to understand distribution uniformity, spread uniformity or CV (%) by spinner disc speed was plotted against effective spread width for all vanes (fig. 3.5). For this analysis, the mean single-pass patterns were used to generate the simulated overlap patterns using the progressive method outlined in ASABE Standard S341.3 (ASABE Standards, 2009) for spread widths between 10 and 30 m at 5-m increments. The minimum CV at the maximum spread width was then selected as the effective spread width at each spinner-disc speed (fig 3.5).

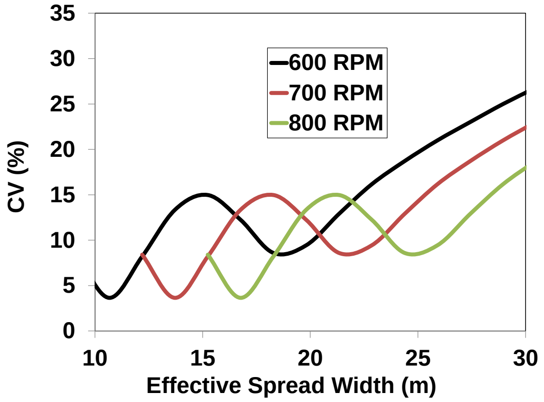


Figure 3.5. Example of CV (%) versus effective spread width (m) at the three spinner-disc speeds of 600, 700 and 800 rpm of the fertilizer spreader. The three points indicated the minimum CVs and thereby effective spread width at the respective spinner disc speed.

Finally, standardized distribution patterns were created by dividing single-pass patterns by the mean application rate based on the simulated overlap data (Fulton et al., 2005). These standardized patterns permitted a direct comparison of design and possible shifts for the various treatments.

3.5 Results and Discussion

3.5.1 Physical Properties

Table 3.2 presents the composite potash (KCl) sample analysis for bulk density, particle density, mean diameter and Granular Spread Index (GSI). Overall, the GSI was greater during stationary testing versus pan tests. Mean bulk density for the pan testing (1153.3 kg m^{-3}) was found to be greater than stationary testing (1073.2 kg m^{-3}). Mean particle density was the same for all tests. However, the mean diameter of 3.0 mm for potash was greater during pan testing than the stationary tests (2.6 mm).

Table 3.2. Average physical properties for Potash (KCl) used during this study. Standard deviation presented in parenthesis.

Physical Property	**Stationary Testing**	**Standard Pan Testing**
Mean Bulk Density (kg/m^3)	1073.2 (4.6)	1153.3 (0.8)
Mean Particle Density (kg/m^3)	1980.0 (0.0)	1980.0 (0.0)
d_{50} (mm)	2.6 (0.1)	3.0 (0.1)
Granular Spread Index (GSI)	30.3	24.6

3.5.2 Stationary Tests

3.5.2.1 Vane Design Influence on Overall Particle Exit Point off the Disc

Table 3.3 represents overall material concentration by all the treatments within a vane, captured in different zones of the collection device. Zones 2 through 6 represent the controlled zones whereas Zones 1 and 7 were uncontrolled. Zone1 captured an insignificant amount of material in it over all three spinner disc speeds. Also no significant differences were observed in Zone 1 as impacted by the vane design over three spinner disc speeds. Zone 7 represented the uncontrolled material flow and detailed discussion of which is followed in Section 3.5.3.2. Zones 2 and 6 captured material similarly with no significant differences over three spinner disc speeds indicating symmetry. Zones 3 and 5 also behaved in a similar fashion with no significant differences in them over three speeds.

Table 3.3. Overall average of percent material mass (%) measured by zone for each vane design by spinner disc speed at feed rate of 224 kg ha^{-1}.

Vane	Disc Speed (rpm)	Zone No. 1	2	3	4	5	6	7
		Average Mass (%)						
1	600	0.8^{jk}	4.7^{ij}	22.0^{f}	22.4^{ef}	22.6^{ef}	6.4^{hi}	21.2^{f}
2		0.6^{jk}	4.6^{ij}	25.1^{cdef}	26.2^{cde}	26.7^{bcd}	4.5^{ijk}	12.2^{g}
3		0.4^{k}	3.8^{ijk}	27.9^{bc}	23.5^{def}	30.4^{ab}	3.7^{ijk}	10.3^{gh}
4		0.4^{k}	4.5^{ijk}	30.4^{ab}	24.2^{cdef}	33.3^{a}	4.1^{ijk}	3.1^{ijk}
1	700	0.6^{jk}	4.0^{ijk}	20.5^{g}	22.8^{fg}	20.9^{g}	5.5^{i}	25.8^{bcdef}
2		0.8^{jk}	4.0^{ijk}	24.0^{efg}	28.7^{abcd}	25.4^{cdef}	4.0^{ijk}	13.1^{h}
3		0.4^{k}	2.7^{ijk}	27.3^{bcde}	23.3^{fg}	29.2^{abc}	2.5^{ijk}	14.6^{h}
4		0.5^{k}	4.4^{ij}	29.4^{ab}	25.0^{def}	31.7^{a}	4.0^{ijk}	5.0^{i}
1	800	0.8^{h}	3.1^{h}	17.9^{f}	20.2^{ef}	18.3^{f}	4.3^{h}	35.4^{a}
2		0.9^{h}	3.1^{h}	23.5^{de}	28.2^{bc}	25.2^{cd}	3.2^{h}	15.9^{f}
3		0.7^{h}	1.7^{h}	25.3^{cd}	26.6^{bcd}	26.7^{bcd}	1.8^{h}	17.3^{f}
4		0.5^{h}	4.3^{h}	27.5^{bcd}	23.5^{de}	29.7^{b}	3.6^{h}	10.9^{g}

Means denoted by same letters are not significantly different (level of confidence α = 95%) within a specific disc speed.

3.5.2.2 Controlled Material Flow

Zones 2 through 6 represented controlled material flow on the disc / vanes. Table 3.4 presents the mean mass distribution and comparisons for Zones 2 through 6. It was indicated that majority of the material concentration was in Zones 3 through 5. Vane 2 captured the greatest amount of material in Zone 4 compared to other three vane designs irrespective of the spinner disc speed. Vanes 1 and 2 behaved similarly as they received more material in Zone 4 compared to 3 and 5. Vanes 3 and 4 captured more material in Zones 3 and 5 compared to Zone 4, indicating more material being pushed out. ANOVA results indicated no significant differences occurred between the material captured in Zones 3 and 5 ($p>.05$) for four vanes at 700 and 800 rpm, indicating they behaved similarly. However, at 600 rpm, significant differences occurred between Zones 3 and 5 and more material was applied to right side. Zones 2 and 6 showed no significant differences over all the speeds. Vanes 1 and 2 captured material similarly in Zones 3 through 5 at 600 rpm as no significant differences were observed. With the increase in speed to 700 and 800 rpm for Vanes 1 and 2, differences occurred between Zones 3, 4 and 5. Zone 4 captured more material compared to Zones 3 and 5. Table 3.5 illustrates the material captured in Zones 2 through 6 and comparisons within specific zones. It could be noticed that significant differences could be observed on particle exit points off the vane with the increase in speed and vane design. For Zone 2, Vane 1 captured the maximum material at 600 rpm with 6.0% and Vane 3 with the least 2.1% at 800 rpm. In Zone 3, Vanes 3 and 4 showed the maximum material in them followed by Vanes 1 and 2 irrespective of the disc speed. Vane 2 resulted in the greatest amount of material captured in Zone 4 having 33.9% at 800 rpm compared to other three vane designs. Zone 5 behaved the same like as that Zone 2 with Vanes 3 and 4 capturing more material than Vanes 1 and 2. Zone 6 behaved similarly like the Zone 2 with Vane 1 capturing the greatest amount of material 8.3% at 600 rpm and least by Vane 3 showing 2.2% at 800 rpm.

Table 3.4. Average percent material captured by zone when considering only Zones 2 through 6 or zones where controlled distribution occurred at feed rate of 224 kg ha^{-1}.

Vane	Disc Speed (rpm)	Zone No.				
		2	3	4	5	6
		Average Mass (%)				
1	600	6.0^{hi}	28.2^{ef}	28.6^{def}	28.9^{cdef}	8.3^{h}
2		5.3^{i}	28.8^{def}	30.1^{cde}	30.6^{cde}	5.2^{i}
3		4.3^{i}	31.2^{cd}	26.3^{fg}	34.0^{ab}	4.2^{i}
4		4.7^{i}	31.5^{bc}	25.1^{g}	34.5^{a}	4.3^{i}
1	700	5.4^{hi}	27.8^{fg}	30.9^{cde}	28.4^{efg}	7.5^{h}
2		4.7^{i}	27.8^{fg}	33.3^{abc}	29.5^{def}	4.6^{i}
3		3.1^{i}	32.2^{abc}	27.4^{fg}	34.3^{a}	3.0^{i}
4		4.7^{i}	31.2^{bcd}	26.4^{g}	33.6^{ab}	4.2^{i}
1	800	4.9^{gh}	28.1^{ef}	31.6^{abc}	28.7^{def}	6.7^{g}
2		3.7^{hi}	28.2^{ef}	33.9^{a}	30.3^{cde}	3.9^{hi}
3		2.1^{i}	30.8^{cd}	32.4^{abc}	32.5^{abc}	2.2^{i}
4		4.8^{gh}	31.1^{bc}	26.5^{f}	33.5^{ab}	4.1^{hi}

Means denoted by same letters are not significantly different (level of confidence α = 95%) within a specific disc speed.

Table 3.5. Average percent material captured by zone when considering only Zones 2 through 6 or zones where controlled distribution occurred at feed rate of 224 kg ha^{-1}.

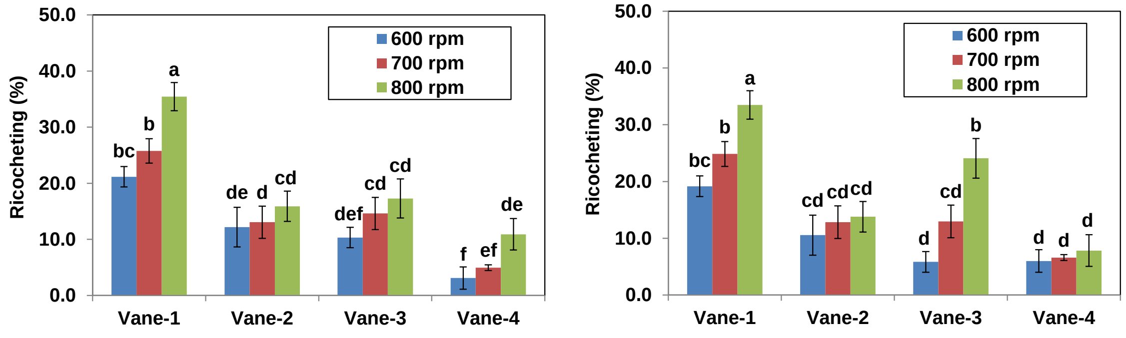
Vane	Disc Speed (rpm)	Zone No.				
		2	3	4	5	6
		Average Mass (%)				
1	600	6.0^{a}	28.2^{c}	28.6^{def}	28.9^{c}	8.3^{a}
2		5.3^{ab}	28.8^{bc}	30.1^{cde}	30.6^{bc}	5.2^{bc}
3		4.3^{abc}	31.2^{a}	26.3^{fg}	34.0^{a}	4.2^{cd}
4		4.7^{ab}	31.5^{a}	25.1^{g}	34.5^{a}	4.3^{cd}
1	700	5.4^{ab}	27.8^{c}	30.9^{bcd}	28.4^{c}	7.5^{a}
2		4.7^{ab}	27.8^{c}	33.3^{ab}	29.5^{c}	4.6^{cd}
3		3.1^{bc}	32.2^{a}	27.4^{efg}	34.3^{a}	3.0^{de}
4		4.7^{ab}	31.2^{a}	26.4^{fg}	33.6^{a}	4.2^{cd}
1	800	4.9^{ab}	28.1^{c}	31.6^{abc}	28.7^{c}	6.7^{ab}
2		3.7^{abc}	28.2^{c}	33.9^{a}	30.3^{bc}	3.9^{cde}
3		2.1^{c}	30.8^{ab}	32.4^{abc}	32.5^{ab}	2.2^{e}
4		4.8^{ab}	31.1^{ab}	26.5^{fg}	33.5^{a}	4.1^{cde}

Means denoted by same letters are not significantly different (level of confidence α = 95%) down the column within a specific zone.

3.5.2.3 Ricocheting

The particle ricocheting generated an undesired and uncontrolled scenario. Figure 3.6 represents the uncontrolled material flow behavior i.e. percentage of material ricocheting (overall mean mass distribution percentage by all treatments within a vane, represented by Zone 7 in table 3.3) for all the vane designs. The design of vane top edge impacted the level of ricocheting by fertilizer particles thereby amount of uncontrolled distribution of material. The forward, upward facing top edge at 32° of Vane 1 generated the highest mean uncontrolled material flow on average 26.6%. Whereas top edge tapering at 15° facing backwards in Vane 2 resulted in rearwards rotation to the particles contacting it, thus increased their ability to be picked up the next vane thereby resulted in reducing overall mean ricocheting to 13.1%. The Vane 3 also generated comparable overall mean ricocheting of 14.2% as Vane 2 (p>.4568), due to their similar profiles. The fourth Vane 4, generated the least amount of overall mean ricocheting (6.6%). It was because that it had an enclosed rectangular U-section and constant height which was also comparatively less than the other three vane designs. The uncontrolled part of the flow ranged between 6.6% (Vane 4) and 26.6% (Vane 1) with the maximum difference of 20% between the upper and the lower values.

3.5.2.4 Impact of Increase in Spinner Disc Speed on Ricocheting



(a) (b)

Figure 3.6. Representation of ricocheting % (i.e. uncontrolled material flow) ± 1 SD for all the four vane shapes, a. 224 kg ha^{-1} b. 448 kg ha^{-1}. Means denoted by the same letters are not significantly different (α = 95%).

The results indicated that as disc speed increased, so did the fertilizer collected, indicating increased ricocheting with disc speed. All vane designs exhibited statistically significant results for ricocheting in Zone-7 (p<.0001). It was observed that as material concentration in Zone-7 increased for all vane designs, the percent of potash collected in the remaining six zones decreased relatively. For all spinner disc-speeds, Vane 1 generated the maximum ricocheting, whereas Vane 4 resulted in the least. The results indicated that increase in feed rate did not significantly impact (p>.05) the concentration of material captured within different zones however, the increase in spinner disc speed did significantly impact distribution between zones (table 3.3). The Vane 1 generated the highest level of ricocheting ranging between 20.2% at 600 rpm up to 34.5% at 800 rpm. Vane 2 maintained consistent level of ricocheting; 11.5% at 600 rpm, 12.9% at 700 rpm and 14.8% at 800 rpm. Vane 3 generated 8.1%, 13.8% and 20.7% at 600, 700 and 800 rpm. The Vane 4 had the lowest ricocheting ranging from 4.6% at 600 rpm, 5.8% at 700 rpm and 9.4% at 800 rpm. The increase in spinner disc speed increased ricocheting. On increasing the disc speed from 600 to 700 rpm; 25.5%, 13.8%, 70.7% and 27.0% increase in ricocheting was observed for Vanes 1, 2, 3 and 4. Whereas, an increase of 71.0%, 30.5%, 156.0% and 105.7% was generated in ricocheting on increasing the disc-speed from 600 to 800 rpm. The concentration of material captured in the Zones 1 and 4 determined vane contribution to the center peak of spread distribution pattern (table 3.3). Less than 1% of potash was captured in Zone-1 for all vane designs, indicating little contribution to the center peak and overall pattern. Zones 3 and 5 for Vanes 3 and 4, received more material in comparison to Zone-4 representing that more material was pushed on the outer ends in spread distribution pattern indicating reduced center peak of spread distribution pattern.

3.5.3 Distribution Pattern Make-Up

The EDEM simulation results provided clarification that two unique distributions existed for this spreader. The two patterns were superimposed on each other; controlled and uncontrolled (fig. 3.6). The controlled flow pattern was desired and could be altered using known methods for setting the divider, vane angle and disc speed. The uncontrolled component of material distribution was primarily caused by ricocheting off the vanes and could not be altered through hardware adjustments. It caused material application directly behind the spreader along with increasing the center peak of the spread pattern, the undesired one. While conducting the static tests for the single-pass spread patterns, an interesting observation was made that regardless of altering the flow divider position, the spread pattern did not change shape. Therefore single-pass pattern was divided into two individual patterns. The one pattern consisted of potash landing up to 4.88 m traversely behind the spreader (fig. 3.7) and termed the uncontrolled aspect of distribution. The other called was termed the controlled distribution and is desired. Simulation results indicated that the center peak never changed regardless of the divider adjustments thereby representing ineffectiveness of the divider adjustments for changing the spread pattern shape. However, the controlled pattern responded to adjustments made in divider position.

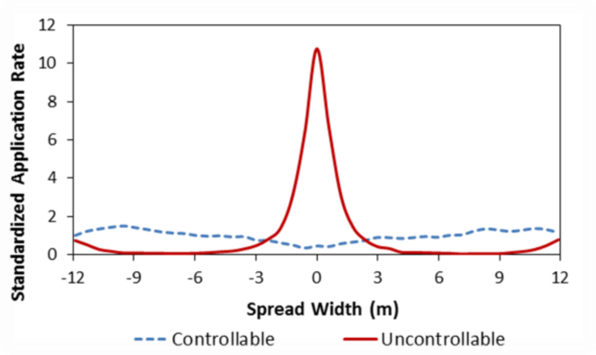
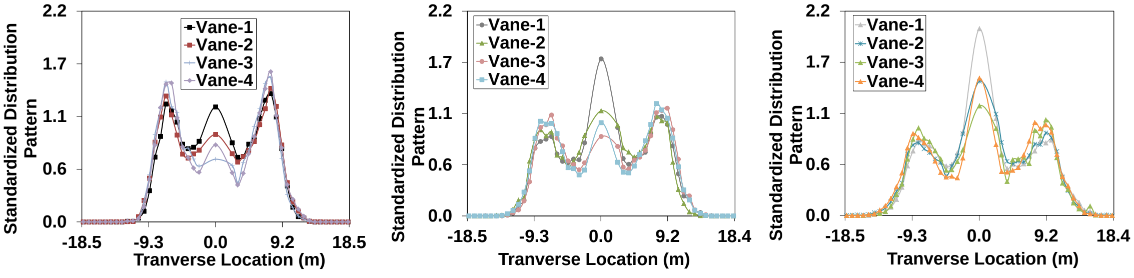


Figure 3.7. Depiction of the two spread patterns which make up the overall single-pass spread pattern based on EDEM simulations. One pattern represents the controlled material distribution and the other uncontrolled.

3.5.4 Standard Pan Tests

3.5.4.1 Standardized Distribution Pattern Analysis

Figure 3.8 represents the mean standardized distribution patterns for all the vane designs. The spread distribution pattern varied by vane design. The trends obtained at both the feed rates were comparable with minor shifts on either edge. Increasing the feed rate to 448 kg ha^{-1}, the center peak also increased. The reason was that ricocheting caused the particles to be applied along the spreader centerline (+/- 2.3 m). Vane 1 resulted in the highest center peaks in comparison to other vanes due to reason that it resulted the greatest ricocheting over three disc speeds compared to other three vane designs as presented in Table 3.3. Vane 1 generated 21.2%, 25.8% and 35.4% ricocheting over disc speeds of 600, 700 and 800 rpm which were significantly higher than the other three vane designs (Table 3.3). It was because that when particles contacted the top edge of Vane 1, particle ricocheting off the vane occurred thereby resulting in high center peaks. On comparing Vane 1 with 2, Vane 2 had a smaller center peak (fig. 3.8) and more effective spread width (Table 3.6). The reason was that Vane 2 had 15° tapered top edge facing backwards such that when the particles contacted it, rearward rotational motion was generated thereby increasing their ability to be picked up by the next vane. Also the material captured in Zones 3, 4 and 5 for Vane 2 was greater compared to Vane 1 (Table 3.4) indicating more controlled material behavior in Vane 1 than Vane 2. Due to reduction in center peak, more material was pushed to the outer edges of the spread distribution pattern thus indicating more effective spread width. As disc speed increased, the peaks on either edge reduced while the center peak increased in magnitude. This can be explained on the basis that with increase in disc speed particle ricocheting off the vanes increased, which caused greater material concentration to fall along the centerline behind the spreader and thus reduced concentration on the either edges.



(a) **(b)** **(c)**

Figure 3.8. Mean average standardized distribution patterns for all vanes; designated as 1, 2, 3 and 4 at feed rate of 224 kg ha^{-1} over spinner disc speeds of a) 600 rpm, b) 700 rpm and c) 800 rpm. Each curve in the graph represents mean of three replications. Transverse location represents the position of pans on the spread width, 0 represents the point of travel of the spreader with negative points on the left hand side of the spreader and positive points on right hand side of the spreader.

3.5.4.2 Impact of Vane Design on Effective Spread Width

The vane shape impacted the fertilizer particle interaction on vane-disc assembly and ultimately resulting spread pattern and effective spread width. The disc speed was the primary parameter which controlled the spread width but vane design also impacted the maximum spread width for a fertilizer product. The effective spread width varied by vane design on spinner-disc speeds of 600, 700 and 800 rpm. The effective spread width increased with spinner disc speed for all the vane designs as shown (fig. 3.8). For the Vanes 1, 2, 3 and 4, an increase of 16.7% in the effective spread width was observed on increasing disc-speed from 600 to 700 rpm. A 7.1% gain was observed on increasing the speed from 700 to 800 rpm for vanes 1, 2 and 3. However the Vane 4 had the greatest increase of 14.3% in effective spread width with spinner disc-speed increase from 700 to 800 rpm. It was because of enclosed rectangular U-section in Vane 4 and reduced exit height in comparison to other vanes, due to which the velocity vector of exiting particles had greater magnitude of horizontal component than the vertical component which assisted in projecting the particles to the maximum distance thus the greatest effective spread width. It was observed that at disc speed of 600 rpm, effective spread width of 18.3 m and 21.3 m at 700 rpm was obtained for all vane designs. The point of interest was at 800 rpm as the trend obtained was not the same, 22.9 m effective spread width was generated by Vanes 1, 2 and whereas 24.4 m for Vane 4.

Table 3.6. Impact of increase in spinner disc speed on effective spread width for the Vanes 1, 2, 3 and 4.

Disc Speed (rpm)	Vane 1,2 and 3	 4
	-------------------Spread Width (m)	-------------------
600	18.3	18.3
700	21.3	21.3
800	22.9	24.4

3.5.4.3 Vane Design Impact on Spread Uniformity

Figures 3.9 and 3.10 represent the impact of vane design on spread uniformity and plots for which were generated using simulated overlap analysis. The spread uniformity varied over the effective spread width by vane design. It was found that Vane 2 resulted in the lowest and most consistent spread uniformity over all disc speeds. Spread uniformity improved with spinner disc speed for both Vane 3 and 4. For Vane 1, spread uniformity deteriorated the most with increase in disc speed. At 800 rpm for Vane 1, the CV versus spread width indicated that spread uniformity did not follow the expected trend of shifting the curve to the right as disc speed increased. Around 20 m, this curve somewhat leveled out and quickly increased and there was not much offset to the right for the 800 rpm curve versus 700. This result was not found in the other three vanes. One explanation for this was the 35% or more level of ricocheting caused by Vane 1 at this high disc speed deteriorating the spread uniformity.

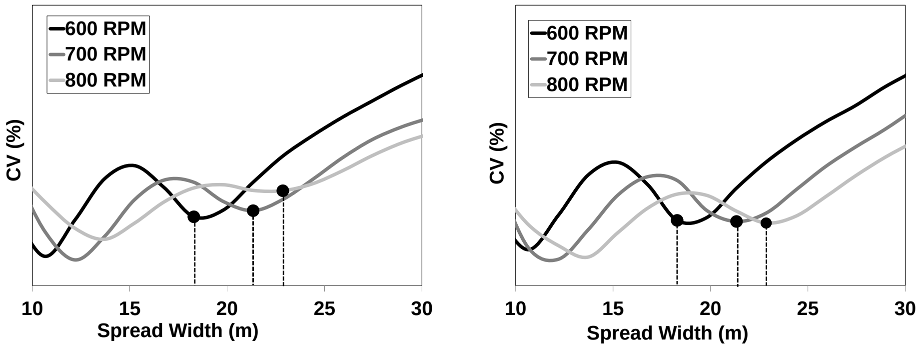


Figure 3.9. Plot of spread uniformity (CV; %) versus effective spread width for Vane 1 (left) and Vane 2 (right) over different disc speeds.

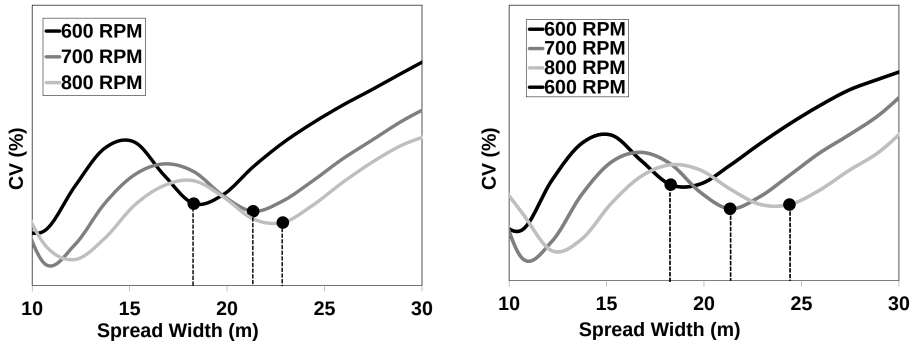


Figure 3.10. Plot of spread uniformity (CV; %) versus effective spread width for Vane 3 (left) and Vane 4 (right) over different disc speeds.

3.5.4.4 Particle Flow Behavior

The high speed video analysis provided insight which confirmed the level of ricocheting varied by vane design. Most noticeable was the high level of ricocheting by Vane 1 (fig. 3.11) with a noticeable reduction for Vanes 2, 3 and 4. The high speed videos indicated that the ricocheting was primarily due to fertilizer flow intersecting the top edge of the vane with minimal resulting from bouncing off the spinner-disc. For all vane designs most of the material was flowing along vane bottom at a height of carriage bolts above the vane base. The bolt heads influenced the minimum exit height of particles as they left the vane. The bolt heads located at the bottom of the vane mounting it to the disc, kept material flow above the bolt heads as particles flew across the vane face. The open end profile Vanes – 1, 2 and 3 tended to generate greater magnitude of vertical velocity vector component (fig. 3.12) thus reduced effective spread width whereas the Vane 4 had an enclosed rectangular cross section (U-shaped) which reduced the exit height of particles while increasing the horizontal, exit velocity vector component thereby increasing the maximum distance travelled and effective spread width (fig. 3.11). As the particles were not always intercepted immediately by the vanes, they acquired some initial velocity through collisions with the disc, before the succeeding vane caught them. Furthermore, when potash particles contacted the top edge of vane, particle ricocheting off was observed.

A significant amount of material was found to be ricocheted off by the vanes as compared to the discs. It was observed that particles contacting the vane edges had more lateral and vertical velocity in comparison to particles contacting the discs. The backward tapered top edge of Vane 2 generated a rearward rotational velocity for the particles contacting it. The result was that these particles would fall back onto the disc and intercepted in the next vane thus increased the vane efficacy. The particles that contacted the disc only did not travel far thereby being applied directly behind the spreader. The Vane 4 was the most aggressive design in terms of describing the interaction of fertilizer particles with the vane on initial contact. This interaction generated more ballistics resulting in fertilizer particles breaking into fine versus the other three vane designs.

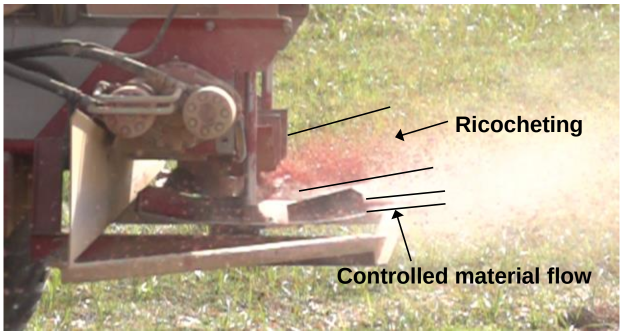


Figure 3.11. Illustration of material flow and ricocheting off Vane 1.

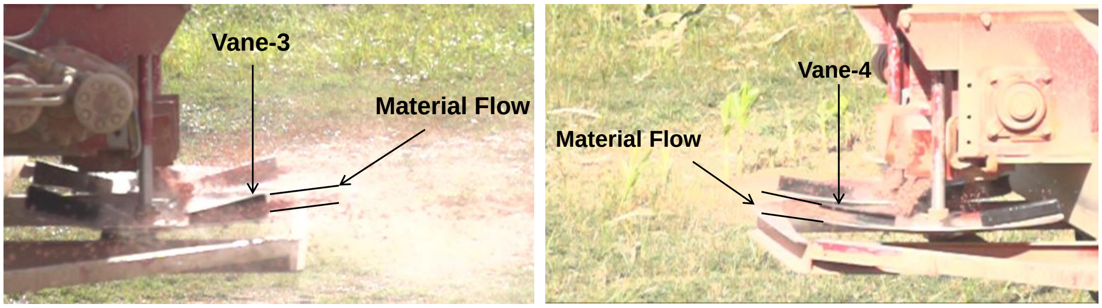


Figure 3.12. Material flow off Vane 3 (left) versus Vane 4 (right). Note the absence of ricocheting for Vane 4.

3.6 Summary

Two types of fertilizer flow were discovered generating two distinct spread patterns superimposed to form the overall spread pattern; a) controlled and b) uncontrolled material flow. The controlled material was desirable and could be regulated making through hardware adjustments such as flow divider position, gate height and disc/vane design. Whereas the uncontrolled flow caused material application directly behind the spreader as it was difficult to manage. This study showed that the level of ricocheting was significantly impacted by top edge of the vane thereby impacting the amount of uncontrolled material off the vanes. The level of ricocheting was significantly impacted by top edge design of vane. The forward upward facing top edge of the Vane 1 generated the maximum overall mean ricocheting of 26.6% when the particles contacted it. However, the rearward facing top edge of the Vane 2 resulted in backward rotation on the particles contacting it thereby reducing overall mean ricocheting in half (13.1%). Due to similarity in the profiles of Vanes 2 and 3, Vane 3 generated comparable overall mean ricocheting 14.2% to Vane 2. The Vane 4 generated the least ricocheting of 6.6%.The ricocheting increased with spinner disc speed. The result of ricocheting was that these particles were applied along the spreader centerline thus increasing the center peak of spread distribution pattern. Particle exit behavior depended on the vane shape as Vanes 3 and 4 resulted in more material concentration in Zones 3 and 5 compared to material captured by Vanes 1 and 2, thereby indicating more material being pushed out by enclosed U-sections of Vanes 3 and 4 than open profile Vanes 1 and 2. The controlled material exit behavior represented that Zones 2 and 6 behaved similarly and likewise Zones 3 and 5. Vane 2 resulted in consistent distribution uniformity across all disc speeds. The effective spread width increased with the spinner disc speed. The increase in spinner-disc speed from 600 to 700 rpm increased the effective spread width by 3.0 m regardless of the vane design. Vane 4 at 800 rpm, generated the greatest effective spread width of 24.4 m compared to 22.9 m obtained for Vanes 1, 2 and 3. Shortened vane exit height resulted in greater magnitude of the horizontal velocity vector thereby creating a wider effective spread width. In conclusion, vane design impacted spread uniformity that can affect long-term soil fertility levels if poor distribution occurs over time.

Chapter 4 COMPARISON OF CHEMICAL VERSUS PHYSICAL METHODS FOR MEASURING NUTRIENT CONCENTRATION

4.1 Abstract

Blended fertilizers are commonly used in the US as a soil/crop nutrient source using dual disc spinner spreaders. However, due to variation in physical properties, there can be issues of non-uniform spread which could lead to deviation from the desired nutrient pattern. Therefore, the objective of this study was to determine nutrient concentration across the swath while applying a 10-26-26 blend using dual disc spinner spreader. In order to determine the phosphorous oxide (P_2O_5) and potassium oxide (K_2O) concentration within a fertilizer sample, two methods were used; a) chemical and b) manual separation. The P_2O_5 and K_2O concentration data obtained through the chemical method was consistently lower than the physical method. However, the nutrient concentration patterns for P_2O_5 and K_2O generated similar trends for both methods by an average difference factor of 1.15.

4.2 Introduction

The fertilizers are essential for crop production. Basically there are two types of fertilizers a) Single Product b) Blends. Single product fertilizers such as urea (46-0-0), potash (0-0-60) supply only one nutrient however the blends like 13-13-13, 17-17-17 can provide all three macronutrients N, P_2O_5 and K_2O at once as per the crop and soil requirements. Therefore use of blended fertilizers overcomes the number of multiple passes that one has to make while using single product fertilizers. The dual disc spinner spreaders being simple and cost effective are commonly used to spread granular fertilizers. Over the past few years, spreader manufacturers have increased the spread widths up to 21-30 m. With the increase in spread widths, the blended fertilizer application can promote risk of segregation due to variation in physical properties of the constituents of blend. The non-uniform fertilizer application coupled with repeated field traverses over years using automatic guidance can cause streaking in the field. Therefore it is essential to determine nutrient concentration across the swath after spreading the fertilizer to look for any deviations from the target. Two methods were implemented for determination of nutrient concentration; chemical analysis conducted within a lab and a physical method. The specific objectives of this investigation were to 1) determine nutrient concentration across the swath using chemical and physical methods and 2) compare and contrast chemical and physical methods.

4.3 Methodology

4.3.1 Chemical Method

The fertilizer samples collected in pans after spreading the blend 10-26-26 using dual disc spinner spreader, were ground using a mortar and pestle. The mortar and pestle were thoroughly cleaned after grinding each sample. After grinding, samples were put back in their respective bags and sealed. Standard Inductively Coupled Argon Plasma Spectrophotometer (ICAP) was used to determine the P_2O_5 and K_2O concentration of each sample. A 0.5 g sample was required to determine P_2O_5 and K_2O. The pans near the far ends on both sides of swath received very less material and weighed lower than 0.5 g.

Due to this limitation, the chemical analysis was conducted only for the inner portion of the swath; -10.7 to 9.1 m.

The ground fertilizer samples were extracted with ammonium citrate at a pH of 7. The ammonium citrate was prepared using Di-sodium EDTA (Ethylene Di-amine Tetra Acetic Acid) and Di-basic ammonium citrate. The 0.5 g of fertilizer samples were weighed and put in labeled jars corresponding to pan number with jars sealed tightly. Afterwards, 100 ml of ammonium citrate was added to each jar and sealed again. In order to extract the samples, sealed jars were placed in shaker water bath (Magni Whirl Constant Temp Bath US Patent No. 2813, Blue M-B-2729-Q-189) at 65°C for a duration of one hour while shaking at 200 rpm. The shaker was designed such that jar contents continuously bathe the inner surface of jar in hot water. Jars were then removed from the shaker and cooled to 20-25^{0}C in the laboratory at ambient temperature. The extracted samples were filtered in flasks using Whatman#42 filter paper. Distilled water was then added to each flask to bring the total volume up to 100 ml. The flasks tops were sealed using plastic wraps and then turned upside down for thoroughly mixing the samples.

Then 10 ml of these samples were then placed in vials and labeled accordingly. The samples collected in vials were then run on the ICAP for determining the percentage concentration of P_2O_5 and K_2O. Afterwards the jars, vials and flasks were washed in distilled water, then in a hydrochloric acid bath and again washed in distilled water twice to thoroughly clean and remove any leftover samples.

The chemical method involved extractions using ammonium citrate at 65ºC while maintaining 200 rpm of water bath. It included use of expensive chemicals and time constraint due to extraction of maximum six possible samples in water bath. Also the original samples could not be retained for future reference while using chemical method. So manual separation of DAP and potash was done and percent nutrient concentration determined for phosphorous oxide (P_2O_5) and potassium oxide (K_2O) as detailed in the following section 4.3.2.

4.3.2 Physical Method

The physical method involved manually separating DAP and Potash particles of the blend (10-26-26) samples. The cubical shaped containers were constructed using paper cardboard with their tops open. The paper sheets were folded such as to make rectangular plates with edges on all four sides to hold the fertilizer sample and a hole in middle to allow the separation of DAP from potash. The fertilizer sample collected in a pan was put in a plate, then DAP and potash separated using wooden bars. Separated DAP and potash particles were weighed individually. In order to determine the percentage concentration of phosphorous oxide (P_2O_5) and potassium oxide (K_2O), equations 4.1 and 4.2 were generated and used.

$$\mathrm{P2O5\%} = \frac{a*0.46*100}{c} \tag{4.1}$$

where

P_2O_5 = percentage of phosphorous oxide

a = mass of DAP at a given pan location (g)

c = total mass of sample collected at a given pan location (g)

0.46 = Phosphorus Oxide (46%) in DAP

$$\mathrm{K2O\%} = \frac{b*0.60*100}{c} \qquad (4.2)$$

where

K_2O = percentage of potassium oxide

b = mass of potash at a given pan location (g)

c = total mass of sample collected at a given pan location (g)

0.60 = Potassium Oxide (60%) in Potash

4.3.3 Inequality Ratio

The inequality ratios were calculated in an attempt to reduce the differences between physical and chemical methods. The inequality ratios were calculated using the sum total of nutrient concentrations for P_2O_5 and K_2O across the swath for the physical method divided by the sum obtained through the chemical method.

4.3.4 Statistical Analysis

A statistical analysis was conducted to compare and contrast the chemical and physical methods. The mean, standard deviation and percentage differences were also calculated for comparisons.

4.4 Results

Table 4.1 represents the percent nutrient concentration values generated for $P_2O_5$and K_2O by chemical method. A and B indicated the results obtained by two different people running the same sample using the chemical analysis. The target nutrient concentration was 26% for $P_2O_5$and K_2O. A and B, both obtained similar results which were lower than the expected concentration of 26% for $P_2O_5$and K_2O respectively. The chemical method generated consistently lower nutrient concentrations for $P_2O_5$and K_2O versus the physical method. Table 4.2 confirmed the low nutrient values for $P_2O_5$and K_2O than the target concentration of 26%.

Table 4.1. Results of nutrient concentration conducted by two different people (labeled A and B) in the lab on the same sample using the chemical method.

Fertilizer Sample (10-26-26)	---------- A ----------		---------- B ---------	
	P_2O_5 (%)	K_2O (%)	P_2O_5 (%)	K_2O (%)
1	22.2	20.2	23.1	20.5
2	21.6	19.7	22.6	20.3

Table 4.2. Nutrient concentration results for running three samples twice using the chemical method.

Fertilizer Sample (10-26-26)	----- Replication-1 ------		----- Replication-2 -----	
	P_2O_5 (%)	K_2O (%)	P_2O_5 (%)	K_2O (%)
1	23.1	19.3	22.8	18.9
2	21.8	20.1	21.5	20.3
3	22.5	21.7	21.7	22.4

The differences for P_2O_5 between two methods ranged between 3.6-4.3% at feed rate of 224 kg ha^{-1} and 1.8 - 3.2% for 448 kg ha^{-1} (Table 4.3). Similarly for K_2O, the observed differences between two methods ranged between 3.9 - 4.6% at 224 kg ha-1 and 1.8 - 2.6% over 448 kg ha^{-1}. P_2O_5 concentration for the chemical method was 4.3%, 3.6% and 3.6% lower than the physical data at a feed rate of 224 kg ha^{-1} and spinner disc speeds of 600, 700 and 800 rpm, respectively. At a feed rate of 448 kg ha^{-1}, P_2O_5 concentration obtained through the chemical method was 3.2%, 4.0% and 1.8% lower than the physical data at 600, 700 and 800 rpm, respectively. The chemical method was found to be more variable in determining nutrient concentration compared to the physical method. In general, the standard deviations for the chemical method were higher in magnitude compared to physical method (Table 4.3).

Table 4.3. Mean P_2O_5 and K_2O concentrations determined using the chemical and physical methods with standard deviation presented in parenthesis. The difference between the two methods is also presented in the last two columns.

Feed Rate (kg ha^{-1})	Disc Speed (rpm)	Chemical Method (%)		Physical Method (%)		Difference between the two methods (%)	
		P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
224	600	21.9 (2.7)	22.0 (3.1)	26.2 (2.4)	25.9 (3.0)	4.3	3.9
	700	22.3 (2.7)	23.0 (2.7)	25.9 (2.2)	26.2 (2.9)	3.6	3.2
	800	21.8 (2.3)	22.3 (3.2)	25.4 (1.4)	26.9 (1.8)	3.6	4.6
448	600	23.5 (2.8)	22.6 (3.1)	26.7 (2.7)	25.2 (3.6)	3.2	2.6
	700	22.1 (1.6)	24.1 (2.3)	26.1 (1.9)	26.1 (2.4)	4.0	2.0
	800	24.2 (2.0)	24.2 (2.1)	26.0 (1.5)	26.0 (2.0)	1.8	1.8

At a feed rate of 224 kg ha^{-1}, the K_2O concentration data was 3.9%, 3.2% and 4.6% lower than the physical data over 600, 700 and 800 rpm, respectively. For a feed rate of 448 kg ha^{-1}, 2.6%, 2.0% and 1.8% variations were observed between the chemical and physical data at 600, 700 and 800 rpm, respectively. As chemical method generated consistently lower values compared to physical method, mean equality ratio of 1.15 was calculated and multiplied with original chemical data to result final chemical data as presented in figure 4.1. It can be noticed that trends obtained between original chemical, final chemical and physical values were similar.

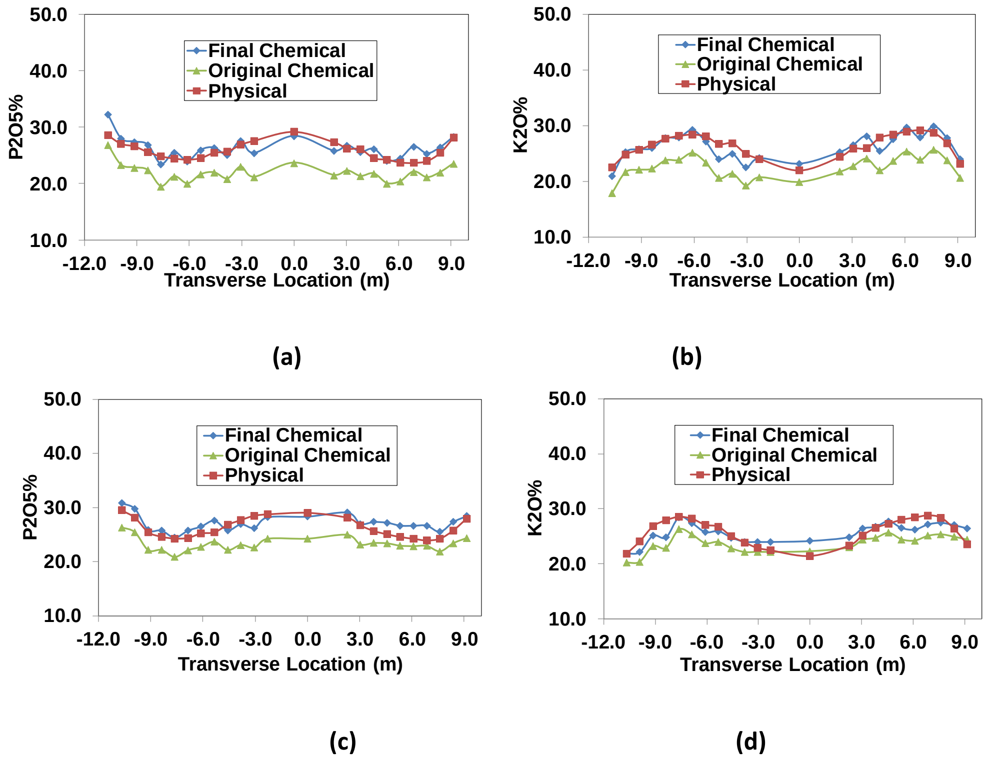


Figure 4.1. Comparisons between original chemical, final chemical and physical data for P_2O_5 and K_2O at two feed rates 224 kg ha^{-1} (a and b) and 448 kg ha^{-1} (c and d).

4.5 Summary

Compared to manually separating individual constituents, the chemical analysis generated consistently lower nutrient concentration values for P_2O_5 and K_2O. P_2O_5 and K_2O concentration values followed similar trends with an average difference factor of 1.15 existing between the two methods.

Chapter 5 POTENTIAL OF FERTILIZER SEGREGATION DURING APPLICATION USING SPINNER-DISC SPREADER

5.1 Abstract

Granular blended fertilizers are commonly applied using spinner-disc spreaders in the U.S. with spread widths between 60 and 100 ft. Today, uniformity of spread is important as growers and custom applicators attempt to implement site-specific management and utilize GPS-based guidance systems which permit equipment to follow the same field traverses over time. However, variation in physical properties of the N, P and K components of blended fertilizers make it difficult to spread them uniformly plus segregation could occur. Therefore, an investigation was conducted to understand the potential of fertilizer segregation during application with a spinner disc spreader. A series of standard pan tests were performed for evaluating nutrient distribution for a blended fertilizer (10-26-26). Treatments included two feed rates (224 and 448 kg ha^{-1}) and three spinner disc speeds (600, 700 and 800 rpm). Results indicated that application of the blended fertilizer resulted in non-uniform spread of the nutrients. Distinct nutrient patterns were generated for the different constituents; "W" shaped for P_2O_5 and "M" for K_2O regardless of feed rate and spinner disc speed. An increase in spinner disc speed widened the maximum transverse distance travelled by particles however it was not equal in magnitude for DAP and potash highlighting segregation. The level of segregation increased with spinner disc speed ($p<.05$) but not with feed rate ($p>.05$).

5.2 Introduction

Spread distribution uniformity is a key goal when applying fertilizers to obtain maximum crop yield and minimize environmental issues. Fertilizers are available as single product such as potash (0-0-60) and urea (46-0-0) or in blended forms (e.g. 13-13-13; 20-20-20; 5-20-20). Blended fertilizers have several advantages compared to single products. Bulk blending helps in providing a practical and economical way to produce crops therefore blends constitute a total of 70% of the total solid fertilizers sold in the U.S. (Formisani, 2005). Blended fertilizer application is economical as it helps in reducing the number of passes across fields in comparison to single product fertilizer application (Yule and Pemberton, 2009) where multiple passes might be required. This practice of using blended fertilizers avoids excess nutrients, which potentially could enter the environment (Miserque et al., 2008). Even though blended fertilizer application has several advantages, segregation of individual components during handling or spreading is a potential problem (Hoffmeister et al., 1964; Hofstee and Huisman, 1990; Bridle et al., 2004; Bradley and Farnish, 2005). Segregation represents the un-mixing of fertilizer constituents (e.g. N, P_2O_5, K_2O) during handling and field application (Hoffmeister et al., 1964; Achorn, 1984). Blended fertilizer can consist of different particle sizes along with different shapes and densities which can cause segregation (Hart, 1998) and segregation is the primary cause of uneven distribution in the field. A fertilizer blend may be initially mixed such that the individual constituents are uniform throughout the volume. However, segregation occurs due to separation of particles into distinct zones by particle size, shape and density (Maynard, 2012). Physical segregation of blended fertilizers may result in different distribution patterns for individual nutrients varying rates over the applied areas (Jensen and Pesek, 1962a).

Various factors exist that cause segregation. A number of researchers have conducted studies in order to determine the effect of particle size on segregation during spreading of fertilizers. Bridle et al. (2004), Bradley and Farnish (2005) and Tang and Puri (2007) indicated that segregation occurred during spreading due to differences in particle sizes of the blended fertilizer. Williams (1976) suggested that a blend with a mean particle diameter larger than 100 µm and variation of more than 30% can cause segregation. Miserque et al. (2008) found that the variation in particle sizes caused segregation as bigger particles tended to be thrown further across the swath while smaller ones landed directly behind the spreader during spreading. They also concluded that variation in particle size and density are the major parameters affecting spread patterns. In other studies (Hofstee and Huisman, 1990; Miserque and Pirard, 2004), it was found that blends should be produced with similar particle size or 10% variation or less in particle size to reduce the segregation. Pircon et al. (1964) suggested that compaction can be one way to reduce segregation. Secondly they recommended that if round shaped particle are selected for the blend, segregation could be reduced as they form rhombic array.

The shape of fertilizer particles has been found to have minimum effect on segregation (Hoffmeister et al., 1964; Miserque and Pirard 2004; Miserque et al., 2008. However, Pircon et al. (1964) detemined that particle size contributed towards segregation because friction factor is intimately related to the particle size. They also indicated that fertilizer particles with similar friction factors reduce segregation in blended products. The particles having irregular shape are more prone to segregation than spherical particles (Tang and Puri, 2007). Jha et al. (2008) reported that percent segregated fines were higher (59%) for angular particles as compared to spherical particles. Spread pattern and segregation of fertilizer particles also depend on their breaking strength (Hofstee, 1992). He also reported that urea had a breaking force of less than 15 N. Consequently, urea was not sufficiently hard enough resulting in particle size reduction, sometimes to powder, when impacting the spinning disc and vanes. This resulted in smaller fines and powder particles landing directly behind the spreader.

5.3 Sub-objectives

The present research is focused on understanding potential segregation of granular fertilizer using spinner disc spreaders. The objectives of this study were to 1) compare and contrast, nutrient distribution patterns with increase in feed rate and spinner disc speed for a blended fertilizer using a spinner-disc spreader, and 2) evaluate the impact of increase in feed rate and spinner disc speed on level of segregation for a blended fertilizer across the swath width.

5.4 Materials and Methods

A commercially available spinner-disc spreader (fig. 3.1; Chandler Equipment Company, Gainesville, GA USA) was used in this study. Hydraulically controlled dual rear spinner discs and stainless steel mesh conveyor chain were standard on the spreader. Four equally spaced vanes (Vane 2 featuring a tapered backwards top-edge at 15° as described in fig. 3.2a and 3.2b of Chapter-3) were mounted on discs. The reason behind using Vane 2 was that it reduced the ricocheting by 50% compared to the Vane 1 being supplied by the manufacturers on the spreaders. Also, Vane 2 resulted in consistent lowest CVs compared to the other 3 vane designs. The spinner discs were concave in shape, 0.60 m in diameter, 0.04 m height and nominal a 9.3 degree exit angle at the periphery. Proportional hydraulic valves (Brand Hydraulics, Omaha, NE) with pulse width modulation maintained hydraulic flow for conveyor chain and spinner discs. A John Deere 7230 tractor was used to pull the spreader and was equipped with a Raven SmartTrax guidance system using RTK correction and an Envizio Pro display (Raven Industries Sioux Falls, SD USA). The Envizio Pro and associated rate controller provided conveyor and spinner disc speed management based on user input parameters. The flow divider on the rear of spreader helped in splitting material flow and control delivery location onto each disc.

Treatments included two feed rates of 224 and 448 kg ha^{-1} and spinner disc speeds of 600, 700 and 800 rpm. Standard pan testing was conducted at the EV Smith Research Center, Shorter, AL using a 10-26-26 blend following ASABE Standard S341.3 (ASABE Standards, 2009) for determining spread distribution patterns and uniformity. Ground speed was kept constant at 12.9 km h^{-1} for all treatments. The spreader hopper was filled to 40-50% capacity and experiments were conducted on days when sustained wind speed was less than 8 km h^{-1} (ASABE Standards, 2009). The test site was flagged for 49 uniformly spaced pans at 0.8 m increments on a level field (slope <2%). Pans on either side of the center pan were removed to allow the tractor pass unobstructed. Collection pans had dimensions of 50.8-cm long x 40.6-cm wide x 10.2-cm tall with a 5.1-cm tall and 10.2 cm x 10.2-cm grid. Material collected in pans was placed in labeled bags and sealed after weighing (Adventure Pro, OHAUS) for calculating application rates and computing single-pass and simulated overlap patterns.

5.4.1 Determination of Physical Properties of Fertilizers

Bulk samples were collected at random in plastic bags from the spreader hopper during tests. An *in-situ* bulk density instrument (Berckes Manufacturing, Canby, MN) was used to determine bulk density of the blend 10-26-26. Particle size analysis was carried out on 500 g samples using a Camsizer (Model 216753, Retsch Technology GmbH, Germany). Particle size was reported as d_{16}, d_{50} and d_{84} (d_x: x is the fraction weight passing the sieve of mesh d) to computed the Granular spread index (GSI).

5.4.2 Data Analysis

Mass of material collected in the collection pans was converted to an application rate (kg ha^{-1}) and was calculated using the mean mass of material collected in pans for each transverse position. The progressive method (ASABE Standards, 2009) was used to generate simulated overlap patterns. The mean application rate, standard deviation and coefficient of variation (CV) were also calculated using the simulated overlap passes. Standardized mass distribution patterns were plotted by dividing average application rate from the simulated overlap passes (Fulton et al., 2005) for each transverse position. Standardization helped comparing and contrasting patterns for different application rates.

At a 95% confidence level, an analysis of variance (ANOVA) was conducted using the general linear model (GLM) procedure with SAS (Statistical Analysis Software, SAS Inst., NC, 9.2) to determine statistical differences between nutrient concentration values for P_2O_5 and K_2O. The ANOVA analysis compared nutrient concentration at feed rates of 224 kg ha^{-1} and 448 kg ha^{-1} over disc speeds of 600, 700 and 800 rpm. Multiple comparisons were also carried out using Tukey Kramer procedure at the 95% confidence interval to determine if differences existed for all combinations.

5.5 Results and Discussions

5.5.1 Fertilizer Physical Properties

Table 5.1 presents the physical properties measured for the bulk samples collected during testing. The granular spread index (GSI) for potash was the greatest (22.8) compared to di-ammonium phosphate-DAP (14.2) indicating greater size variability in potash. GSI for the blend was 19.1. GSI values of greater than 10 are considered to cause segregation (Miserque and Pirard, 2004), therefore DAP and potash generated possibility of segregation due to greater GSI's than 10. DAP had the greatest median diameter (d_{50}) of 3.2 mm followed by potash and the blend (d_{50}=3.0mm). Also DAP particles were more spherical (0.95) compared to potash (0.85), indicating DAP to be near round shaped particles.

Table 5.1. Measured physical properties for the 10-26-26 blend along with individual constituents consisting of Di-ammonium Phosphate (DAP) and Potash (KCl). Standard deviation presented in parenthesis.

Physical Property	**Product**	**Mean (Std. Dev.)**
Mean d_{50} (mm)	DAP	3.2 (0.1)
GSI[a]	DAP	14.2
Sphericity	DAP	0.95
Mean d_{50} (mm)	Potash (KCl)	3.0 (0.1)
GSI[a]	Potash (KCl)	22.8
Sphericity	Potash (KCl)	0.85
Mean d_{50} (mm)	10-26-26	3.0 (0.1)
GSI[a]	10-26-26	19.1
Mean Bulk Density (kg m^{-3})	10-26-26	1009.2 (0.0)
Sphericity	10-26-26	0.91

1) GSI-Granular Spread Index
2) d_{50} represents the median particle size

5.5.2 Single-Pass Nutrient Distribution Patterns

The nutrient distribution patterns for DAP and potash are presented in Figure 5.1. The horizontal line represents the perfect target nutrient concentration of 26% for DAP and potash. As symmetrical pattern provides uniform fertilizer distribution and therefore considered desirable. However, the DAP spread pattern was “W” shaped and “M” for potash; deviating from the target indicating possibility of hardware improvements on spreader by manufacturers. These patterns for DAP and potash are undesirable as they result in non-uniform material distribution. The concentration of P_2O_5 and K_2O applied at the pattern center varied and deviated significantly from the expected 26%.

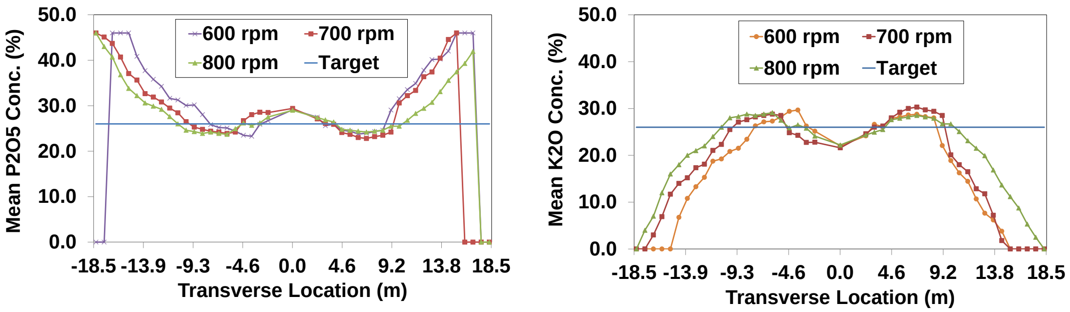


Figure 5.1. Nutrient concentration patterns for P_2O_5 (left) and K_2O (right) at a feed rate of 224 kg ha^{-1}. Transverse location represents pan positions at different locations across the swath.

The DAP and potash patterns were consistent over the two feed rates ($p>.05$), indicating no significant differences with increase in feed rate (fig. 5.2). However, with the increase in spinner disc speed variations occurred between patterns for DAP and potash. The ANOVA results indicated significant differences m ($p<.0001$) in potash patterns for the pan transverse pan locations from -17.5 – 17.5. The variation over pan locations at -18.5 and 18.5 m couldn’t be assessed as they didn’t receive any material in them. Also differences were observed for DAP nutrient patterns across the swath between -18.5 – 18.5 m (fig. 5.1). ANOVA results indicated significant differences at all pan transverse locations ($p<.0001$). In order to attain a perfect target nutrient concentration for DAP and potash, higher values needed to be reduced to fill low areas and lower values raised. Relocation of these points might require hardware adjustments such as disc speed, disc/vane shape, and divider position. On comparing the patterns over spinner disc speeds it was observed that the DAP particles were projected to the outer ends of the swath compared to potash granules thereby indicating segregation. DAP being more spherical (0.95) compared to potash (0.85) tended DAP particles to be thrown further.

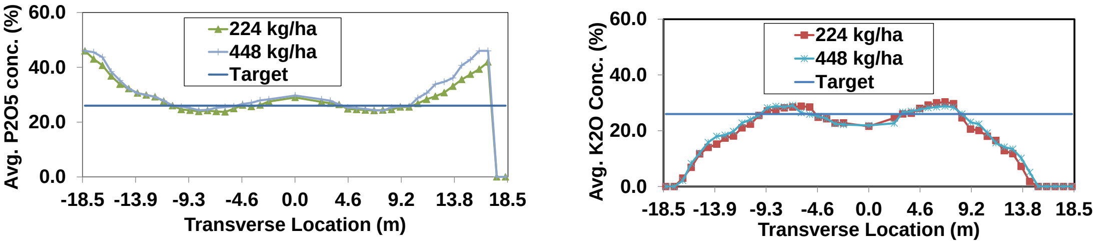


Figure 5.2. Illustration for influence of increase in feed rate on nutrient concentration distribution patterns for percentages of P_2O_5 (left) and K_2O (right). Transverse location represents pan positions at different locations across the swath.

5.5.3 Simulated Overlap Analysis

The results from simulated overlap analysis generated same conclusions as were for single pass “W” shaped pattern for DAP and “M” pattern in potash spread distribution and no variability observed (fig. 5.3). The effective spread widths of 22.9, 25.9, 29.0 m were obtained for DAP and 21.3, 22.9, 25.9 m for potash particles over spinner disc speeds of 600, 700 and 800 rpm respectively (Table 5.2). The interesting point was that the effective spread widths obtained for DAP were greater than potash particles over the each individual spinner disc speed, thus generated segregation while applying blend (10-26-26). It could be observed that DAP generated effective spread width of 22.9 m at 600 rpm whereas potash resulted the same at 700 rpm. Similarly at 700 rpm, DAP generated 25.9 m and potash showed the same at increased speed of 800 rpm. It could be said that there was always a difference of at least 2 m and maximum up to 4 m between the effective spread widths for DAP and potash at specified spinner disc speeds.

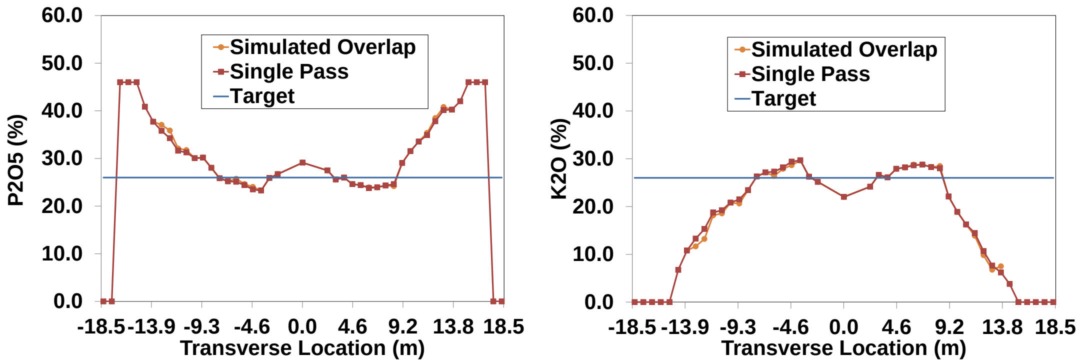


Figure 5.3. Simulated overlap patterns for percentages of P_2O_5 and K_2O. Transverse location represents pan positions at different locations across the swath.

Table 5.2. Effective spread widths determined for DAP and Potash over the different spinner disc speeds.

Spinner Disc Speed (rpm)	Effective Spread Width (m)	
	DAP	Potash
600	22.9	21.3
700	25.9	22.9
800	29.0	25.9

The fertilizer supplier mixed the DAP and potash at a 56.5% / 43.5% proportion by mass to obtain the 10-26-26 blend. However, the actual mass proportions obtained were different from the target as presented in Table 5.3 thereby indicating segregation. For example; 100/0 mass proportion specified that at the particular pan location, only DAP particles were collected in the pan. With the increase in disc speed, DAP particles travelled further compared to potash. Variability existed in the GSI for DAP (GSI = 14.2) and potash (GSI = 19.1) indicating greater size variability in potash component of the blend than DAP. One could notice that material application directly behind the spreader was in the proportions of 63.3/36.7, 63.9/36.1 and 63.0/37.0 for DAP/Potash; which were similar in magnitude over all three spinner disc speeds but higher than intended for DAP and lower for potash. However, moving away from the center (-7.6 to 8.4 m), mass proportions for DAP/Potash were nearing the target at 600 rpm. With the increase in speed, this transverse distance increased to -10.7 to10.7 m suggesting material being pushed more outward with disc speed.

Table 5.3. Mass proportions (%) between DAP and Potash within each collection pan across the swath width for each of the spinner disc speed treatments.

Pan Location (m)	Spinner Disc-Speed (rpm)		
	600	**700**	**800**
	DAP% / Potash%	**DAP% / Potash%**	**DAP% / Potash%**
-18.3	0.0 / 0.0	100.0 / 0.0	100.0 / 0.0
-17.5	0.0 / 0.0	100.0 / 0.0	93.5 / 6.5
-16.8	100.0 / 0.0	95.0 / 5.0	88.5 / 11.5
-16.0	100.0 / 0.0	88.5 / 11.5	80.0 / 20.0
-15.2	100.0 / 0.0	80.6 / 19.4	73.5 / 26.5
-14.5	88.8 / 11.2	77.0 / 23.0	70.0 / 30.0
-13.7	82.0 / 18.0	71.0 / 29.0	66.5 / 33.5
-13.0	77.8 / 22.2	69.3 / 30.7	65.0 / 35.0
-12.2	74.5 / 25.5	67.0 / 33.0	63.5 / 36.5
-11.4	68.8 / 31.3	64.1 / 35.9	60.0 / 40.0
-10.7	67.9 / 32.1	61.8 / 38.2	56.5 / 43.5
-9.9	65.3 / 34.7	57.6 / 42.4	53.5 / 46.5
-9.1	65.6 / 34.4	55.0 / 45.0	52.8 / 47.2
-8.4	61.0 / 39.1	53.9 / 46.1	52.0 / 48.0
-7.6	56.2 / 43.8	53.0 / 47.0	52.6 / 47.4
-6.9	54.8 / 45.2	52.6 / 47.4	52.0 / 48.0
-6.1	54.6 / 45.4	52.0 / 48.0	51.5 / 48.5
-5.3	53.0 / 47.0	52.6 / 47.4	54.2 / 45.8
-4.6	51.0 / 49.0	58.0 / 42.0	56.9 / 43.1
-3.8	50.5 / 49.5	60.9 / 39.1	55.8 / 44.2
-3.0	56.3 / 43.8	62.1 / 37.9	57.0 / 43.0
-2.3	58.1 / 41.9	62.0 / 38.0	59.8 / 40.2
0.0	63.3 / 36.7	63.9 / 36.1	63.0 / 37.0
2.3	59.7 / 40.3	58.9 / 41.1	59.6 / 40.4
3.0	55.6 / 44.4	56.7 / 43.3	58.4 / 41.6
3.8	56.5 / 43.5	56.3 / 43.7	57.4 / 42.6
4.6	53.5 / 46.5	52.4 / 47.7	53.9 / 46.1
5.3	53.0 / 47.0	51.5 / 48.5	53.5 / 46.5
6.1	51.7 / 48.3	50.0 / 50.0	53.0 / 47.0
6.9	52.1 / 47.9	49.6 / 50.4	52.6 / 47.4
7.6	52.9 / 47.1	50.4 / 49.6	53.0 / 47.0
8.4	53.5 / 46.5	59.0 / 41.0	53.5 / 46.5
9.1	63.2 / 36.8	64.8 / 35.2	55.4 / 44.6
9.9	68.5 / 31.5	66.5 / 33.5	55.4 / 44.6
10.7	72.9 / 27.1	70.0 / 30.0	58.2 / 41.8
11.4	75.9 / 24.1	72.5 / 27.5	61.5 / 38.5
12.2	82.2 / 17.8	79.1 / 21.4	63.9 / 36.1
13.0	87.3 / 12.8	81.3 / 19.6	66.8 / 33.2
13.7	87.5 / 12.5	87.9 / 12.1	71.9 / 28.1
14.5	94.0 / 6.0	96.9 / 3.1	77.3 / 22.7
15.2	100.0 / 0.0	100.0 / 0.0	81.4 / 18.6
16.0	100.0 / 0.0	0.0 / 0.0	85.4 / 14.6
16.8	100.0 / 0.0	0.0 / 0.0	91.2 / 8.8
17.5	0.0 / 0.0	0.0 / 0.0	96.1 / 3.9
18.3	0.0 / 0.0	0.0 / 0.0	100.0 / 0.0

5.5.4 Level of Segregation

Table 5.4 represents the influence of sample type (P_2O_5 vs K_2O), increase in spinner disc speed, pan location and interactions between them on level of segregation. It could be interpreted that sample type caused significant differences on the level of segregation as P_2O_5 concentration formed “W” and K_2O formed “M” shaped patterns as discussed in Section 5.5.2. The increase in spinner disc speed caused significant differences on level of segregation ($p = 0.0452$). The target nutrient concentration was 26% both for P_2O_5 and K_2O. However, variations were there from the intended rate, indicating segregation. The level of segregation was not pronounced (Table F.23) near the center of swath (-10.7 – 10.7 m) for P_2O_5 as the percentage of P_2O_5 neared the target, however away from the center, the level of segregation increased as variations from the intended rate got intense. Similarly for potash, the level of segregation was lower near the center, however noticeable variations from the target could be observed away from the center. Significant differences were also observed to be caused due to pan location ($p = 0.0013$). The pans on the ends did not receive potash as they could not travel farther due to their lower sphericity (0.85) compared to DAP (0.95) The interactions between sample-speed and speed-location did not result in significant differences on level of segregation. However the interaction between sample-location caused significant differences.

The increase in feed rate did not significantly impact the level of segregation for P_2O_5 and K_2O concentration over all the transverse pan locations across the swath. The p-values > .05 from ANOVA results (discussed in Table F.24) illustrated no significant differences with the increase in feed rate. It can therefore be said that fertilizer spread distribution can be conducted over the lower feed rate of 224 kg ha^{-1} which can prove economical.

Table 5.4. Representation of the influence of various parameters on the level of segregation.

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr>F**
Sample[1]	1	7959.83	7959.83	133.63	<.0001
Speed[2]	2	382.0.09	191.05	3.21	0.0452
Location[3]	44	5580.084	126.84	2.13	0.0013
Sample*Speed	2	159.83	79.91	1.34	0.2667
Speed*Location	88	3958.36	44.98	0.76	0.9051
Sample*Location	44	12630.06	287.05	4.82	<.0001

1) Sample or individual constituent (P_2O_5 vs K_2O).
2) Spinner disc speed (600, 700 and 800 rpm).
3) Location represents the transverse position of pans across the swath.

5.5.5 Spread Distribution Patterns for Potash Application as Single Product and in a Blend

Figure 5.3 illustrates that the trends obtained for potash application as a single product and in a blend. The ANOVA results indicated that no statistical differences occurred with the increase in feed rate from 224 to 448 kg ha^{-1} (p>.05). However, with the increase in speed, significant differences occurred across the swath over -14.5 – 16.0 m (p<.0001) and no variation was observed over rest of the pan locations, due to the reason that pans did not receive material in them. Another interesting point was that the centre peaks were higher in potash application as a single product compared to blend. The possible answer for differences could be that physical properties of potash varied between the two types of applications. Single product application consisted of GSI with 24.6 and 22.8 for blended application. The greater GSI value in single product application indicated greater variability in particle sizes compared to the blend. Also, the presence of DAP particles in blend might cause variations between two types of applications.

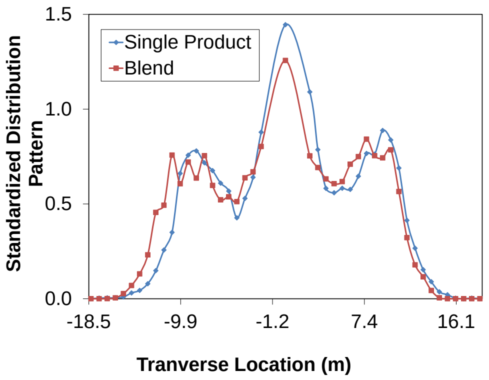


Figure 5.3. Graphical representation of standardized distribution patterns representing potash applied as a blend (10-26-26) versus a single product at feed rate of 224 kg ha^{-1} over spinner disc speed of 800 rpm.

5.6 Summary

The nutrient distribution patterns for application of a blended fertilizer (10-26-26) using a dual disc spinner spreader were characterized and statistically analyzed to determine segregation potential. Non-uniform nutrient spread distribution occurred for this spinner spreader applying the 10-26-26 blend. Deviations from the target nutrient concentration of 26% were measured for bothP_2O_5 and K_2O. Distinctive but different nutrient patterns were generated for the two individual P and K constituents; “W” shaped for P_2O_5 and “M” for K_2O regardless of feed rate and spinner disc speed. No significant differences between the resulting patterns were found between the two feed rates (p>.05). However; the increase in spinner disc speed did increase the width of the nutrient patterns generated causing significant differences (p<.0001) at particular transverse locations. The potash single-pass distribution pattern as an individual product was observed to be slightly different compared to the DAP / Potash 10-26-26 blend. The simulated overlap analysis was conducted to determine the effective spread width for DAP and potash. An increase in spinner disc speed widened the maximum transverse distance travelled by DAP and potash particles. However, the DAP generated effective spread widths of 22.9, 25.9, 29.0 m whereas potash was only 21.3, 22.9, 25.9 m over spinner disc speeds of 600, 700 and 800 rpm, respectively. This result proved further the existence of segregation for the 10-26-26 blend.

Chapter 6 CONCLUSIONS

6.1 Summary

The growing environmental and sustainable focus at the farm level has led the agriculture industry to adopt the 4R’s of nutrient stewardship (Right Rate, Right Source, Right Place and Right Time) while driving researchers to develop better management practices for fertilizers. Over the past decade, spinner-disc spreaders continue to be used for applying fertilizers to crop and pastureland but the effective spread width has increased to 24 to 37 m for many fertilizer applications. However, the increased spread width increases the risk of non-uniform fertilizer distribution and the potential for product segregation when applying blended fertilizers. Therefore, four vane designs were evaluated to understand the influence of vane design on material flow and exit behavior off the vanes as part of Objective 1. A collection device with six zones was used to determine particle exit point and material behavior. Standard pan testing was also conducted to understand the resulting spread patterns for each vane design. A commercial rate controller permitted testing the vanes at two feed rates of 224 and 448 kg ha^{-1} and three spinner disc speeds of 600, 700 and 800 rpm.

Of the overall spread pattern, two distinct patterns were discovered in this research. One pattern was generated through controlled material flow and dispersion with the vane and spinner-disc assembly. The other pattern constituted an uncontrolled material flow or handling. The controlled flow was considered desirable and can be manipulated through hardware adjustments such as flow divider position, disc shape and vane design to achieve uniform spread of material. Conversely, the uncontrolled flow was mostly a result of fertilizer ricocheting off the vanes with the inability to minimize its effect on the overall spread pattern without redesign of the vane or vane-disc assembly. The uncontrolled aspect of material dispersion caused the ricocheted particles to be applied directly behind the spreader creating a concentrated peak at the center of the overall spread pattern. The level of ricocheting was influenced by the top edge of Vane 1. Vane 1 with a 32^{o} forward upward facing top edge, resulted in maximum overall average ricocheting of 26.6% whereas when its top edge was tapered 15º backwards (Vane 2), ricocheting was reduced by approximately 50% (overall average of 13.1%). Therefore, any forward-upward top edges should not be used in vane designs to minimize the ricocheting. Vane 2 and 3 generated similar levels of ricocheting but were similar in design other than Vane 3 had a bent over top edge. The enclosed, U-shaped Vane 4 produced the least mean overall ricocheting of 6.6%.The level of ricocheting increased significantly with the spinner disc speed for all the vane designs. Vane design influenced the particle exit point and thereby the final landing position on the ground. The effective spread width increased by 3.0 m regardless of the vane designs on increasing the spinner-disc speed from 600 to 700 rpm. At a spinner disc speed of 800 rpm, Vane 4 generated the greatest effective spread width of 24.4 m which was expected due to its enclosed rectangular, U-section and smaller height compared to the other vanes. The design of Vane 4 enabled it to impact a more consistent and higher horizontal velocity on the fertilizer particles. Vane design also influenced spread uniformity with Vane 2 generating the most consistent uniformity over all disc speeds. Whereas uniformity deteriorated the most with Vane 1 as spinner disc speed increased.

The second objective aimed in comparing and contrasting chemical and physical methods for analyzing nutrient concentration within a fertilizer sample. Results indicated that the chemical method generated consistently lower nutrient concentration values for P_2O_5 and K_2O compared to the physical process of manually separating individual constituents. However, the nutrient concentration patterns for P_2O_5 and K_2O revealed that the chemical and physical methods generated similar trends illustrating that the chemical method was consistently different in magnitude from the physical method. The average difference factor between the two methods was 1.15 which could be used to adjust the chemical results so they match the physical..

The final aspect of this research focused on determining the segregation potential of a blended fertilizer (10-26-26) applied using a modern dual-disc spinner spreader. Results showed non-uniform application of nutrients illustrating segregation of the blend. Distinct nutrient patterns were produced for the different constituents by this spreader; "W" shaped for DAP and "M" shaped for potash regardless of feed rate and spinner disc speed. The nutrient spread patterns did not vary between the 224 and 448 kg/ha treatments ($p>.05$). However, an increase in spinner disc speed widened the maximum transverse distance travelled by the particles but this increase was not equal in magnitude for DAP and potash ($p<.0001$). Over spinner disc speeds of 600, 700 and 800 rpm, effective spread widths of 22.9, 25.9 and 29.0 m for DAP and 21.3, 22.9 and 25.9 m for potash were obtained, respectively. The level of segregation increased with spinner disc speed ($p<.0001$) but not with feed rate ($p>.05$) as DAP particles travelled further with increase in disc speed. This research illustrated that segregation can occur and needs to be considered in spinner spreader designs and how they are setup for field application.

Uniform spread of fertilizer is important to maximize crop production but also address the environmental concerns to management of nutrients; over-application is not a desirable outcome today. In summary, this research provides valuable insight into how vane design impacts fertilizer deposition and the potential of segregation helping manufacturers and spreader operators understand the consequences of improper design and setups.

6.2 Conclusions

The following conclusions were drawn from this research:

1. Vane design influenced particle exit point and behavior thereby influencing the resulting spread uniformity. Results indicated the presence of two patterns superimposed to create the overall single-pass spread pattern. One pattern was as result of uncontrolled fertilizer handling, mainly due to ricocheting, and the other pattern was the desired, controlled flow and dispersion by the vanes. Improvements up to 50% in the uncontrolled material flow or ricocheting were measured for Vane 2 compared to Vane 1. The level of ricocheting was negatively impacted by the top, 32^o forward-upward facing edge of Vane 1. Vane 2 provided consistent spread uniformity over the spinner disc speeds of 600, 700 and 800 rpm while spread uniformity degraded as disc speed increased. All four vanes produced the same effective spread widths of 18.3 and 21.3 m at 600 and 700 rpm, respectively. However, Vane 4 produced an effective spread width of 24.4 at 800 rpm whereas only 22.9 m by the other three vanes.
2. The chemical method generated consistently lower nutrient concentration for P_2O_5 and K_2O versus manually separating constituents. A nominal difference

factor of 1.15 existed between the two methods indicating that manual sorting was higher on average by 15%.

3. Finally, segregation while applying a 10-26-26 blended fertilizer with a modern dual-disc spinner spreader was documented. The DAP and Potash constituents produced different nutrient concentration patterns with a W-shape for P_2O_5 and M-shaped for K_2O. Increase in spinner disc speed significantly impacted the level of segregation at specific transverse locations, however no difference ($p<.05$) was found between the 224 and 448 kg/ha application rates. Effective spread widths between DAP and Potash were different for the three spinner disc speeds again highlighting the presence of segregation between the constituents during application.

6.3 Opportunities for Future Research

Results of this research call for improvements in fertilizer spreaders to improve spread uniformity. Fertilizer delivery onto the vanes can be researched to enhance the controlled material flow behavior and thereby reducing harsh impact of current spreader designs. In general, current spinner spread designs in the US generate a more vertical flow of material off the divider onto an individual disc-vane assembly. This situation causes a high impact scenario between the vane and fertilizer especially at higher disc speeds. A more gradual introduction of fertilizer to the vane would help reduce impact and the resulting potential for particle ballistics to occur. One suggestion would be to introduce the material more towards the center of the disc where no or little of the vane would impact the fertilizer. Revising the flow of fertilizer onto the vane-disc assembly would require a re-design of the divider and vanes so they work as a system to reduce the level of impact. Other vane designs should be considered and thoroughly tested in the manner presented in this Thesis to determine the “best” vane design to reduce the presence of ricocheting but maintains acceptable spread uniformity over the desired spread widths here in the US.

The design of the collection device which was used during the stationary testing in Chapter 3 should be revised to include more zones. The addition of more zone would permit a higher understanding of the actual exit location of fertilizer off the vane plus may allow a better connection between stationary and standard pan testing. In return, more information about vane design and the specific exit point of fertilizer would be gained.

Other ideas would be the inclusion of optical sensor to provide real-time evaluation of the spread pattern. The testing conducting during this research is time consuming with limited understanding of results. Sensors to provide information on spread could help increase research and development enhancing spinner-disc spreader design here in the US. Further, real-time nutrient analysis of the resulting distribution patterns would ensure spread uniformity of macronutrients there by reducing segregation during field application.

Discrete Element Modeling (DEM) software might help in determining the setup parameters (e.g. divider position and design, disc speed, and vane shape) for a spinner disc spreader and a specific fertilizer. DEM can reduce the time requirement to conduct time-consuming pan testing in order to determine the correct setup for a product. Knowing the physical properties of a fertilizer product or blend, DEM could help optimize the fertilizer product and spreader setup to ensure uniform spread. Further, DEM simulations could help in better understanding particle physics and aerodynamics as they exit the vane and their final landing location. Also, this type of modeling might determine the nature of interactions between particle-to-particle and particle-to-material permitting better insight to component design and how it influences material flow and dispersion. Other insights could include understanding and setups to minimize or eliminate segregation and the proper effective spread width for a product.

REFERENCES

Achorn, F.P. and Border, M.F. 1984. Use of large sized granular fertilizer, situation. *Tennessee Valley Authority Fertilizer Conference:* 60-66.

Antille, D. L., R. Sakrabani, S. F. Tyrrel, M. S. Le, and R. J. Godwin. 2013. Development of organomineral fertilizers derived from nutrient-enriched biosolids granules: product specification. ASABE Paper No. 131620153. St. Joseph, Mich.: ASABE.

Aphale, A., N. Bolander, J. Park, L. Shaw, J. Svec and C. Wassgren. 2003. Granular fertilizer particle dynamics on and off a spinner spreader. *Biosystems Eng*. 85(1): 319-329.

ASABE Standards. 2009. S341.4: Procedure for measuring distribution uniformity and calibrating granular broadcast spreaders. St. Joseph, Mich.: ASABE.

Bartos, J.M., G.L. Mullins, J.C. Williams, F.J. Sikora, and J.P. Copeland. 1992. Water-insoluble impurity effects on phosphorus availability in mono ammonium phosphate fertilizers. *Soil Sci. Soc. Am. J.* 56(3): 972-976.

Borlaug, N. 2008. Fertilizer's role in world food production. The Fertilizer Institute, 820 First Street, N.E., Suite 430, Washingtion D.C. 20002.

Bradley, M.S. and R.J. Farnish. 2005. Segregation of blended fertilizer during spreading: the effect of differences in ballistic properties. *International Fertilizer Society-Proceeding*. 554. ISBN 978-0-85310-190-1.

Bridgwater, J. 1994. Mixing and segregation mechanisms in particle flow. In *Granular material: An interdisciplinary Approach,* ed. A. Mehta. *New York; Springer-Verlag*. 161-193.

Bridle I.A., M.S.A Bradley, A.R Reed, H. AbouChakra, U. Tuzun, I. Hayati and M.R. Phillips. 2004. Non Segregating Blended Fertilizer Development: A new predictive test for optimizing granulometry. *International Fertilizer Society-Proceeding*-547. ISBN 978-0-85310-183-3.

Brinsfield, R.B and J.W. Hummel. 1975. Simulation of new centrifugal distributor design. *Trans. ASAE.* 213-220.

Broder, M.F. 1983. Performance testing of fertilizer application equipment. ASABE Paper No. 83-1503, St. Joseph, Mich.:ASABE. pp: 9085-9659.

Broder, M.F., and Balay, H.L. 1983. Effect of granule size on fertilizer application. *Proceedings of 33rd Annual Meeting of the Fertilizer Industry Round Table.* 90-93.

Brubach, M., and H. Gohlich. 1973. Effect of physical properties of fertilizer on the distribution. *Andtechnik*. 9(10): 289-292.

Burks, T.F., S.A. Shearer, and J.P. Fulton. 2000. Assessment of Fertilizer Application Accuracy With the Use of Navigation Aids. ASAE Paper No. 001154. Annual International Meeting, Midwest Express Center, Milwaukee, Wisconsin, July 9-12.

Carman, K. 1991. The effect of disc peripheral speed and free radius on the distribution pattern in single spinning-disc type spreader. Selcuk University. *J. Agric. Fac*., 2: 75-83.

Chandler Spreaders. 2013. Operations and Parts Manual-30PTT-FLTHEXW. Chandler Equipment Company, Gainesville, GA 30503.

Chen, J.H. 2006. The combined use of chemical and organic fertilizers for and/or biofertilizers for crop growth and soil fertility. *International Workshop on Sustained*

Management of the Soil-Rhizosphere System for Efficient Crop Production and Fertilizer Use. Land Development Department, Bangko-10900, Thailand.

Coetzee C.J and S.G. Lombard. 2011. Discrete element method modeling of a centrifugal fertiliser spreader. *Biosystems Eng*. 109(4): 308-325.

Cunningham, F.M. 1963. Performance characteristics of bulk spreaders for granular fertilizer. *Trans. ASAE.* 6(2):108-114.

Curry D., J. Favier and R.D. Laroche. 2012. A systematic approach to DEM material model calibration. DEM Solutions Ltd., 49, Queen St., Edinburgh EH2 3NH, UK:1-4.

Davis, J.G., K.V. Iversen , M.F. Vigil and R.B. Meyer. 2008. Manure sampling and spreader calibaration: testing our recommendations. *Colorado State University Fort Collins, CO-80523.*

Delgado C.L. 2003. Rising Consumption of meat and milk in developing countries has created a new food revolution. *American Society for Nutritional Sciences. 3166(22):*3907S-3910S.

Delitz, M. 1969. Computations of spinning discs. *Deutsche Agrartechnik.* 19(5):239-242.

Dintwa, E., E. Tijskens, R. Olieslagers, J. D. Baerdemaeker and H. Ramon. 2004. Calibration of spinning-disc spreader simulation model for accurate site specific fertilizer application. *Biosystems Eng.* 88(1): 49-62.

Drahun, J.A. and J. Bridgwater. 1983. The mechanisms of free surface segregation. *Powder Tech.* 36(1): 39-53.

ERS-USDA. 2012. Data Sets: US Fertilizer Use and Price. United States Department of Agriculture Economic Research Service. Available at: www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26727. Accessed 17 March 2013.

FAO. 2012. Feeding the World. Food and Agriculture Organization of the United Nations. *ISBN 978-92-5-106913-4*, Rome, Italy.

Fertilizer Technologies. Available at: www.nutrite.com/catalogues/NUT2011-055_2012_hr_golf_can_en.pdf. Accessed 21 January 2014.

Fulton, J.P., S.A. Shearer, S.F.Higgins, D.W. Hancock, and T.S. Stombaugh. 2005. Distribution pattern variability of granular VRT applicators. *Trans. ASAE.* 48(6): 2053-2064.

Fulton, J.P., S.A. Shearer, T.S. Stombaugh, M.E. Anderson, T.F. Burks, and S.F.Higgins. 2003. Simulation of fixed and variable rate application of granular materials. *Trans. ASAE.* 46(5):1311-1321.

Fulton, J., C. Brodbeck, T.Tyson, A. Winstead and S. Norwood. 2009. Calibrating equipment with variable rate technology. *Precision Agriculture Series Timely Information, Agriculture, Natural Resources and Forestry.* Alabama Co-operative Extension System, Alabama A&M and Auburn Universities. Alabama Precision Ag Extension.

Formisani C. 2005.Trends in Bulk Blending World Wide. A.J. Sackett& Sons Company, Baltimore, Maryland USA.

Galili, N. and Shteingauz,G. 1982. Wide-swath vertical spreader for granular material. *Trans. ASAE.* 25(5): 1195-1203.

Garcia, F.O. 2012. The 4Rs in a Latin American Context: Right Source at Right Rate, Right Time, and Right Place. *Fertilizer Latino Americano Conference and Exhibition. Buenos Aire. FMB-CRU Events.*

Glover, J.W. and J.V. Baird. 1973. Performance of spinner type fertilizer spreaders. *Trans. ASAE.* 16(1): 48-51.

Grift, T.E., G. Kweon, J.W. Hofstee, E. Piron and S.Villete. 2006. Dynamic friction coefficient measurement of granular fertilizer particles. *Biosystems Eng.* 95(4): 507-515.

Hardesty J.O and W.H. Ross. 1978. Factors affecting granulation of fertilizer mixtures. *Industrial and Eng. Chem.* 30(6): 668-672.

Harnby N. 1973. The handling and distribution of granular particles. J. *Agr. Food Chem*. 21(1): 78-82.

Hart J. 1998. Fertilizer and lime materials. *Oregon State University Extension Service*. FG52.

Haynes, R.J. and R. Naidu. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems.* 51(1):123-137.

Heymann, W. 1971. Arbeitsqualität und Streuleistung von Düngerstreumaschinen in Abhängigkeit von der Düngerqualität. Deutsche. *Agrartechnik*. 21(1): 187-191.

Heege, H.J. and W. Hellweg. 1982. Entmischung bezuglich der korngrosse beim verteilen von mineraldunger. *Grundl Landtechnik.* 32 (1):13-19.

Hoffmeister G., S.C. Watkins and J. Silverberg. 1964. Bulk blending of fertilizer material: effect of size, shape and density on segregation. *Agri. and Food Chem.* 12(1): 64-69.

Hofstee, J.W., L. Speelman and B. Scheufler. 1999. Fertilizer Distributors. *CIGR Handbook of Agricultural Engineering.* Vol. III, Plant Production Engineering. St. Joseph, Mich.: ASABE, pp:265-277.

Hoftsee J.W. and W. Huisman. 1990. Handling and spreading of fertilizers Part 1: Physical properties of fertilizer in relation to particle motion. *J. Agri. Eng. Res*. 47(1): 213-234.

Hoftsee J.W. 1992. Handling and spreading of fertilizers Part 2: Physical properties of fertilizer, measuring methods and data. *J. Agri. Eng. Res*. 53(1): 141-162.

Hollmann, W. 1962. Research on the distribution of fertilizer by spinning disc fertilizer distributor. *Dissertation TU-Berlin, Berlin.* pp. 321.

ISO. 1985. ISO 5690: Equipment for distributing fertilizers – Test methods, Part 1: Full-width fertilizer distributors. In ISO Standards Handbook 13, Agricultural Machinery. Geneva, Switzerland: International Organization for Standardization.

Jensen, D.and J. Pesek. 1962a. Inefficiency of fertilizer use resulting from non-uniform spatial distribution. II. Yield losses under selected distribution patterns. *Soil Sci. Soc. Am. Proc*. 26(1): 174-178.

Jensen, D., and J. Pesek. 1962b. Inefficiency of fertilizer use resulting from nonuniform spatial distribution. III. Fractional segregation in fertilizer materials. *Soil Sci. Soc. Am. Proc. Vol.* 26(1): 178-182.

Jha A.K., H. Yi and V.M.Puri. 2006. Segregation in and flowability of blended fertilizers. An ASABE Meeting Presentation, Portland, Oregon, Paper No. 064004, 9-12 July: 1-17.

Jha A.K., J.S. Gill and V.M. Puri. 2008. Percolating Segregation in Binary Size Mixtures of spherical and angular shaped particles of different densities. *Science and Tech*. 26(5): 482-493.

Jha A.K.and V.M. Puri. 2011. Modeling and validation of percolation segregation of fines and coarse mixtures during shear motion. Hosokawa Powder Technology Foundation. *J. Pow. and Par*.29(1): 81-95.

Kampfe, K.F. and H.J. Jaschke. 1982. Relationship between essential physical properties and the eveness of the distribution pattern during the distribution of fertilizer. *Agrartechnik* 32(6): 253-256.

Karnok J.K. 1986. The segregation of homogeneous and blended granular fertilizers from a rotary spreader. *J. Agron*. 78(2): 258-260.

Kirilov P. 2005.Non-caking fertilizers from Ammonium Nitrate and supplementary nutrients. *J. Univ. Chem. Tech. and Metal*. 40(3):209-212.

Larson, B.A., and G.B. Frisvold. 1996. *J. Food Policy*. 21(6): 509-525.

Lawrence, L.R. and J.K. Beddow. 1969. Powder segregation during die filling. *Powder Tech.* 2(1): 253-259.

Lawrence H. G. and Yule I.J. 2007.Modeling of fertilizer distribution using measured machine parameters. *Trans. ASABE.* 50(4): 1141-1147.

Liedekerke P. V., E. Piron, J. Vangeyte, S. Villette, H. Ramon and E. Tijskens. 2008. Recent results of experimentation and DEM modeling of centrifugal fertilizer spreading. *Granular Matter*. 10(4): 247-255.

Liedekerke, P. V., E. Tijskens and H. Ramon. 2009. Discrete element simulations of the influence of fertilizer physical properties on the spread pattern from spinning disc spreaders. *Biosystems Eng*. 102(4): 392-405.

Maynard E. and J & Johnson, Inc. 2012. Avoid Bulk Solids Segregation Problems. *Fluids and Solids Handling. CEP*. 35-39.

McCauley A, C. Jones and J. Jacobsen. 2009. Commercial fertilizers and soil amendments. *Nutrient Management-A self-study course from MSU extension continuing education series.* Montana State University Extension. Publication 449-510.

Marsh, L., G. Mullins, S. Ambler, and R. Heidel. 2003. Manure spreader calibration for rear discharge equipment. Virginia Cooperative Extension Publication 442-004.

Miserque O. and E. Pirard. 2004. Segregation of the bulk blend fertilizers. *Chemometrics and Intelligent Laboratory Systems*.74(1): 215-224.

Miserque O., E. Pirard, Y. Schenkel, O. Mostade and Huyghebaert. 2008. Spreading segregation of blended fertilizers: influence of the particle properties. *Appl. Eng. in Agri*. 24(2): 137-144.

Moshou, D., D. Deprez and H. Ramon. 2004. Prediction of spreading processes using a supervised self-organizing map. *Mathematics and Computers in Simulation.*65 (1): 77-85.

Olieslagers, R.H. Ramon, and J.D. Baerdemaeker. 1996. Calculation of fertilizer distribution patterns from spinning disc spreader by means of simulation model. *J. of Agri. Eng.* 63(2):137-152.

Oldham L.2008. Inorganic fertilizers for crop production. *Mississippi State University Extension Service*. Publication No.2500.

Parish, R. L. and P.P. Chaney 1985. Evaluation of a rotary spreader with a helical cone for drop point control. *Trans. ASAE.* 25(5):1140-1444.

Parish, R.L. 1986. Comparison of spreader pattern evaluation methods. *Appl. Eng. in Agri*. 2(2): 89-93.

Parish, R.L. 1991. Effect of rough operating surface on rotary spreader distribution pattern. *Appl. Eng. Agri. ASAE*. 7(1):61-63.

Parish, R.L. 2000. Spreader rate determination from pattern tests compared with rate calibration. *Appl. Eng.in Agri.* 16(2): 119-120.

Parish, R. L. 2002. Rate setting effects on fertilizer spreader distribution patterns. *Appl. Eng. in Agri.* 18(3): 301-304.

Patterson, D.E. and Reece, A.R. 1962. The theory of the centrifugal distributor, I: motion on the disc, near-center feed. *J. Agri. Eng. Res.* 7(3): 232-240.

Pircon, L.J. de la Puente and S. Mahdu. 1964. Segregation studies of dry blended fertilizers. *Agri. and Food Chem.*: 12 (4): 357-362.

Randall, G.W. and Hoeft, R.G. 1988. Placement methods for improved efficiency of P and K fertilizers. *J. Prod. Agric.* 1(1): 70-79.

Reed W.B. and E. Wacker. 1970. Determining distribution pattern of dry-fertilizer applicators. *Trans. ASAE.* 13(1): 85-89.

Richards, I.R., 1985. Effects of inaccurate fertiliser spreading on crop yield and quality in the UK. Proc. No.240. The Int. Fert. Soc., York, UK.

Rosato A.D., D.L. Blackmore, N. Zhang and Y. Lan. 2002. A perspective on vibration induced size segregation of granular materials. *Chem. Eng. Sci*. 57(1): 265:275.

Sanaeifar, Alrireza and M. J. Sheikhdavoodi. 2012. Evaluating of Broadcasting Uniformity of Centrifugal and Oscillating Granular Broadcasters. *Res. J. Appl. Sc., Eng. and Tech.* 4(15): 2460-2468.

Scharf, P. 2009. Streaky fields and uneven application of N fertilizer. *Nutrient News in Missouri*. 19(2): 10-11. Available at: plantsci.missouri.edu/nutrientmanagement/news.html. Accessed 16 September 2013.

Science Daily. 2013. Available at: www.sciencedaily.com/releases/2013/06/130619195135.html. Accessed 11 April 2014.

Shakhashiri. 2014. Agricultural Fertilizers:Nitrogen, Potassium and Phosphorus. *Chemical of the week.* Available at: scifun.chem.wisc.edu/chemweek/pdf/Agricultural_Fertilizers.pdf. Accessed 29 January 2014.

Smith, G.E. 1961. *Proc Fertilizer Ind. Roundtable,* Washington, D.C. pp. 90-96.

Smith, D.B., M.H. Willcutt, J.C. Doller, and Y. Diallo. 2004. Uniformity of granular fertilizer applications with a spinner truck. *Appl. Eng. Agri.* 20(3): 289-295.

Smith, G.E. 1961. *Proc Fertilizer Ind. Roundtable,* Washington, D.C. pp. 90-96.

Sogaard, H.T. and Kierkegaard. 1994. Yield reduction from uneven fertilizer distribution. *Trans. ASAE.* 37(6): 1749-1752.

Solutions for Agriculture. 2013. Available at: www.fluidfertilizer.com/pdf/Fluid%20Characteristics.pdf. Accessed 15 October 2013.

Speelman, L. 1979. Features of reciprocating spout broadcaster in the process of granular fertilizer application. *Mededelingen Landbouwhogeschool, Wageningen,* 217.

Stewart, L. and Bandel A. 2002. Uniform lime and fertilizer spreading. Maryland Cooperative

Extension. University of Maryland, College Park, MD. EB-254: 1-12.

Stewart, W.M., D.W. Dibb, A.E. Johnston, and T.J. Smyth. 2005. *Agron. J*. 97(1): 1-6.

Tang, P., V.M. Puri, and P.H. Patterson. 2003. Design, development and performance of second generation primary segregation shear cell for size-segregation. Paper presented at Particulate Systems Analysis 2003, Sep. 10-12, Harrogate, U.K.

Tang P. and V.M. Puri. 2007. Segregation quantification of two component particulate mixtures-Effect of particle size, density, shape and surface texture. *Part. Sci. Tech.* 25(6): 571-588.

The Mosaic Company. 2013. Available at: www.mosaicco.com/images/Diammonium_Phosphate.pdf. Accessed 10 June 2013.

Tissot S., O. Miserque and G. Quenon. 1999. Chemical distribution patterns for blended fertilizers in the field. *J. Agri. Eng. Res.* 74(4): 339-346.

Tissot, S., O. Miserque, O. Mostade, B. Huyghebaert, and J.P. Destain. 2002. Uniformity of N-fertilizer spreading and risk of ground water contamination. *Irrig. and Drain.* 51(1): 17-24.

USDA. 2010. Fertilizer use and price in US: Fertilizer Consumption and Use by year: Economic Research Service. Available at: www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx. Accessed 17 January 2013.

USDA. 2013. Average U.S. farm prices of selected fertilizers, 1960-2013. Available at: www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26727. Accessed 15 September 2013.

Virk, S.S, D.K. Mullenix, A. Sharda, J.B. Hall, C.W. Wood, O.O. Fasina, T.P. McDonald, G.L. Pate and J.P. Fulton. 2013. Case Study: Distribution uniformity of a blended fertilizer applied using a variable-rate spinner disc spreader. *Appl. Eng. Agric.* 29(5): 627-636.

Weekend Gardener, monthly web magazine. 2014. Available at: www.weekendgardener.net/organic-fertilizer/types_of_manure.html. Accessed 29 January 2014.

Wells, K. L., Terry, D. L., Grove, J. H., Brinklry, W. E. and Broder, M.F. 1992. Spreading uniformity of granular bulk-blended fertilizer. *Communications in Soil Science and Plant Analysis*. 23(15): 1731-1751.

Welch L.F., A. R. Bertrand and W. E. Adams. 1964. How nonuniform distribution of fertilizer affects crop yields. *Georgia Agric. Res. Bul*. 5(3).

Williams J.C. 1976. The segregation of Particulate materials: A Review. *Powder Tech.* 15(2): 245-254.

Yildirim,Y., and M. Kara. 2003. Effect of vane height on distribution uniformity in rotary fertilizer spreaders with different flow rates. *Appl. Eng. Agri.* 19(1): 19-23.

Yildirim, Y. 2006. Effect of vane number on distribution uniformity in single-disc rotary fertilizer spreaders. *Appl. Eng. Agri.* 22(5): 659-663.

Yildirim, Y. 2008. Effect of vane shape on fertilizer distribution uniformity in single-disc rotary fertilizer spreaders. *Appl. Eng. in Agri.* 24(2): 159-163.

Yildirim,Y., and M. Kara. 2012. Effect of different vane combinations on fertilizer distribution uniformity with various flow rates in spinning disc broadcasters. *J. Agri. Sciences* (18): 54-62.

Yule I. and J. Pemberton. 2009. Spreader testing for mixing and segregation of blended fertilizers. ASABE Paper No. 096380. St. Joesph, Mich.: ASABE.

Yule I. 1996. The effect of fertilizer particle size on spread distribution. NZ Centre for Precision Agriculture, Massey University, Palmerston North, New Zealand: 1-9.

Zhou C. and J. Y. Ooi. 2009.Numerical investigation of progressive development of granular pile with spherical and non-spherical particles. Mechanics of Materials. 41(6): 707-714.

APPENDICES

APPENDIX A: SPREADER SPECIFICATIONS

Figure A.1.Rear view of the agricultural fertilizer and lime spreader used in this research.

Manufacturer	Chandler Equipment Company, Gainesville, GA
Model	30 PPT – FTLH EXW
Length	6.3 m
Fertilizer Payload (Struck Level)	8264.4 kg
Hopper Capacity (Heaped and Tarped)	8.8 m^3
Spinner Motor	Gear motor; 0.05 m diameter shaft
Conveyor Chain	Mesh Type (0.69 m wide)
Recommended Spread Width	21.3 - 30.5 m
Type of Vane	Vane 1 (fig. 3.2a)
Disc type	Concave with 0.60 m diameter, 0.04 m height and 9.3º nominal exit angle
Recommended Spinner Disc Speeds	600 – 800 rpm; depends on spread width and fertilizer type
Motor for Spinner Discs	Brand Hydraulics, Omaha, NE
Encoder Type for determination of conveyor chain speed	DICKEY-john 360 pulses per revolution
Hydraulic Control Valves	Brand hydraulics with pulse-width modulation (PWM) flow regulation

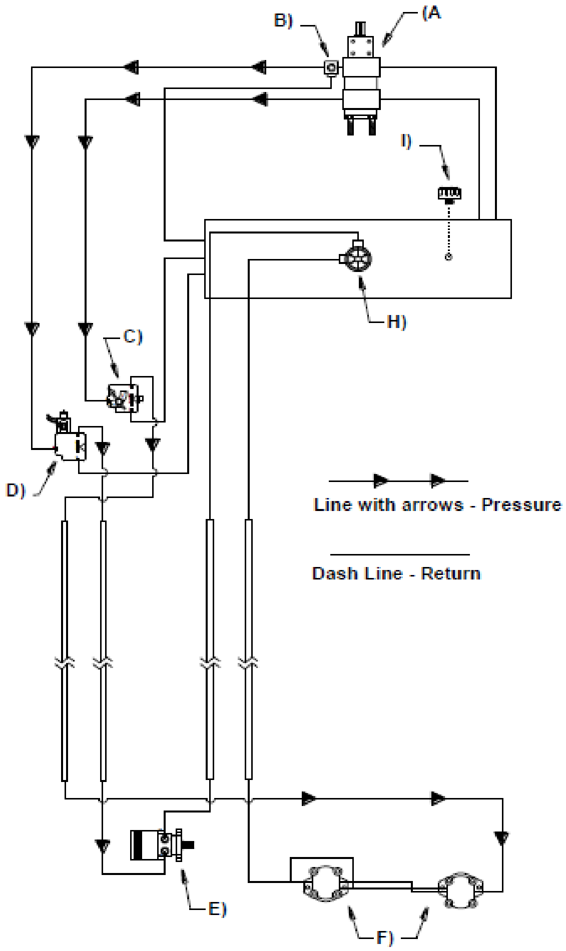


Figure A.2. Hydraulic circuit for the conveyor and spinner discs (Chandler Spreaders, 2013).

Part No.	Description
400-C-209 B	P-2500 Tandem Pump 0.06 m X 0.06 m
400-1-308	Relief valve- Nonadustable-2500 PSI
400-1-313	Flow Control Valve with Built-in-Relief
Options063-0171-846063-0172-19435-02128	Control Valve Raven: 30 GPM PWM Fast Valve Teejet: 30 GPM EXR-4
400-R-106400-R-104	Parker-MB-18-Single Rawson Drive Parker-MB-12-Twin Rawson Drive
400-C-218B	M-2500 2” Gear Spinner Motor
300-1-208	Filter gauge
300-FL-113A	EXW-Filter
400-1-317	Breather Cap

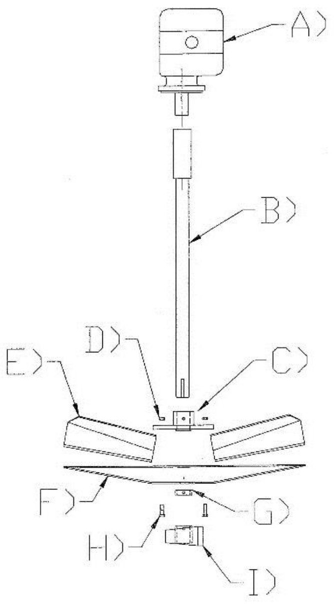


Figure A.3. Exploded view of spinner assembly (Chandler Spreaders, 2013).

Part No.	Description
A. 400-C-218 B	M-2500-0.05 m Gear Spinner Motor
B. 300-1-210	Spinner Shaft M25
300-1-211	Spinner Shaft-Stainless M25
C. 300-FL-112	4 Bolt Spinner Hub
300-FL-112A	4 Bolt Spinner Hub-Stainless
D. 300-FL-114063-0171-846063-0172-19435-02128	0.01 m Hex Head Flange Nut
E. 300-EXW-103400-R-104	F/L EXW H/T Spinner Blades
F. 300-EXW-101	Spinner Disc
300-EXW-102	Spinner Disc-Stainless
G. 300-1-208	Lock Collar
H. 300-FL-113A	.01X.03 m Hex Head Bolt
I. UCP-207-20	Pillow Block Bearing

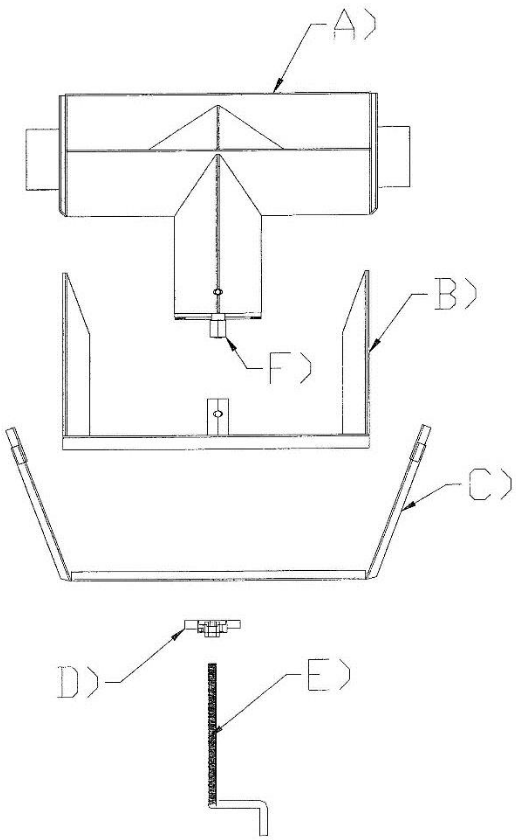


Figure A.4. Exploded view of flow divider assembly (Chandler Spreaders, 2013).

Part No.	**Description**
A. 300-EXW-107	EXW Flow Divider Base
B. 300-EXW-108	EXW Flow Divder Insert
A & B 300-EXW-106	EXW Flow Divder Assembly
C. 300-EXW-109	Flow Divider Bar
D. UCFL-204-10063-0171-846063-0172-19435-02128	0.02 m Flange Bearing
E. 300-FT-012400-R-104	Flow Divider Adjustment Rod
F. 300-FT-013	Flow Divder Nut

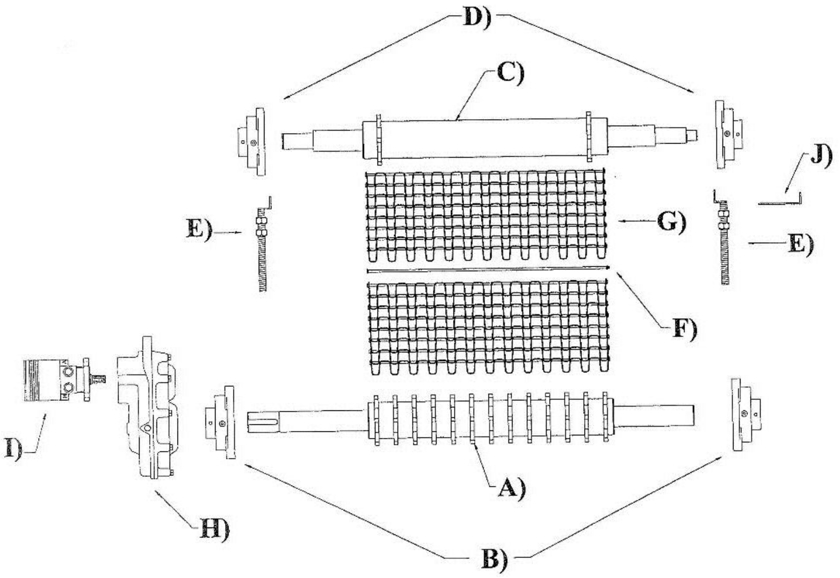


Figure A.5. Conveyor Assembly (Chandler Spreaders, 2013).

Part No.		Description
A.	HWC-R-2434	Rear Roller Assembly
B.	UCF-211-32	Flange Bearing
C.	HWC-F-2434-EXW	Front Roller Assembly-EXW
D.	UCF-208-24063-0171-846063-0172-19435-02128	Flange Bearing
E.	300-FT-008400-R-104	Roller Adjustment Rod
F.	500-3-309	Connecting Pin 0.61 m
G.	500-3-304	Mest Type Chain-0.61 m (7.72 lg)
H.	100-R-1-01	Gear Case - Single
	100-R-2-01	Gear Case – Twin
	100-R-1-01A	Gear Case – Single with Rate Sensor Port
	100-R-2-01A	Gear Case – Twin with Rate Sensor Port
I.	400-R-106	Hydraulic Motor – MB16 (Single Gear
	400-R-104	Hydraulic Motor-MB16 (Twin Gear Case)
F.	300-EXW	Encoder Mounting Bracket

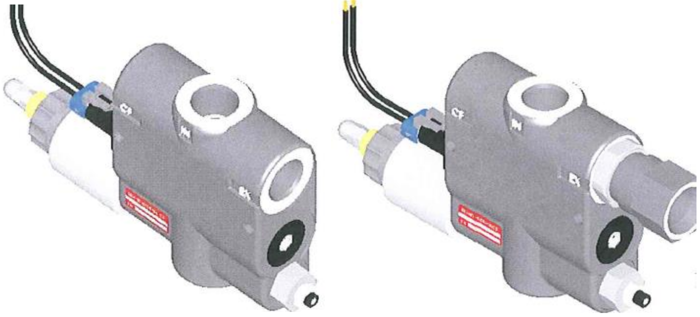


Figure A.6. Electronically adjustable proportional pressure compensated flow controls (EFC). EFC12-10-12 (Left) and EFC12-15-12R22(Right)

Features	
Weight	3.9 kg
Standard Port Size	#12SAE (1-1/16-12)
Filtration	10-Micron
Pulse Frequency	90-115 Hz
Response Time	0.035” Standard dash pot (375 ms)
	0.020” Dash pot (900 ms)
	0.093” Dash pot (175 ms to 350 ms depending on flow
Spool Leakage	50 ml/min@1000 psi on EX port
Coil	12 VDC standard (24VDC)
	9.6 ohms (48 ohms)
	15 watts (15 watts)
	1.0 amp max (0.5 amp max.)

APPENDIX B: TRACTOR SPECIFICATIONS

Figure B.1. John Deere 7230 Tractor.

Part	Description
Manufacturer	John Deere
Model	7230
Enginer Power	99 kW
No. of engine cylinders	6 (6.8 L Displacement)
Cooling System	Dual temperature
Emission Level	Tier 3
Exhaust	Variable Geometry Turbocharger and Exhaust Gas Recirculation
Transmission	16/16 Power Quad Plus Wet Multi-Disc Clutch Hydraulics Pressure and Flow Compensated 110 L/min Pump Flow at 2300 RPM Two 350 Series SCV's; Mechanical with ISO Breakaway Couplers
Steering	Hydrostatic
Brakes	Wet Disc Hydraulic Power
AutoGuidance System	Raven SmartTrax^{TM} using RTK correction

APPENDIX C: RAVEN ENVIZIO PRO SPECIFICATIONS

Figure C.1. RAVEN ENVIZIO PRO and switch pro displaying calibration settings for the spreader

Dimension	0.16 m diagonal measure
Processor	1.6 GHz 32 Bit
RAM Memory	1.0 GB
Internal Storage	2.0 GB
Operating System	Microsoft Windows CE
Integrated Dual Frequency GPS Receiver	
NMEA Output	GGA, GGL, GSA, GSV, RMC, VTG and ZDA
Update Rate	1, 5 and 10 Hz (GSV at 0.2 Hz MAX)
Horizontal Position Accuracy (RMS)	
Signal Point L1	1.5 m
Single Point L1/L2	1.2 m
SBAS	0.6 m
DGPS	0.4 m
RTK-2	1 cm+1 ppm
OMNISTAR VBS	0.6 m
OMNISTAR XP	0.2 m
OMNISTAR HP	0.1 m
USB Data Transfer Ports	2
CANBUS 2.0B COMPATIBLE SERIAL PORTS	2
RS232 SERIAL DATA PORTS	3 (GPS, CONSOLE, AUXILIARY)
Min. Speed Output	0.80 km h^{-1}
Power	24 W Typ.
Switched Output	12 V@1.5A
Density	67.0
Rate Cal	400
Spreader Constant	359
Rate Bump	25

APPENDIX D: MASS OF POTASH COLLECTED BY ZONE FOR THE STATIONARY TESTS IN CHAPTER 3

Table D.1. Mass of potash collected in different zones of collection device for Vane 1.

Rep	Rate (kg ha^{-1})	Disc Speed (rpm)	Collected Mass (g)							Total Mass Envizio (g)	Mass Percentage by Zone (%)						
			Zone No.														
			1	2	3	4	5	6	7		1	2	3	4	5	6	7
1	448	600	799.1	1894.0	6898.0	6971.1	6987.1	2102.5	6099.7	31751	2.5	6.0	21.7	22.0	22.0	6.6	19.2
		800	348.7	1479.6	6900.0	8108.4	6770.0	1746.8	14562.6	39916	0.9	3.7	17.3	20.3	17.0	4.4	36.5
		700	223.5	1316.3	6865.0	8414.4	7010.2	1895.0	10109.4	35834	0.6	3.7	19.2	23.5	19.6	5.3	28.2
	224	700	248.2	1608.8	6843.7	7995.3	6782.6	1916.4	9985.2	35380	0.7	4.5	19.3	22.6	19.2	5.4	28.2
		800	285.1	1181.1	5954.2	6935.1	5933.7	1423.1	12760.7	34473	0.8	3.4	17.3	20.1	17.2	4.1	37.0
		600	393.5	1722.7	7339.9	7558.3	7455.4	2115.4	6980.6	33566	1.2	5.1	21.9	22.5	22.2	6.3	20.8
2	448	700	240.0	1208.0	7351.4	8468.4	7553.9	1827.9	8277.0	34927	0.7	3.5	21.0	24.2	21.6	5.2	23.7
		800	261.8	1110.4	6383.4	7591.5	6468.8	1486.7	12077.6	35380	0.7	3.1	18.0	21.5	18.3	4.2	34.1
		600	284.4	1309.3	7687.5	9201.8	7915.7	2058.4	5562.3	34019	0.8	3.8	22.6	27.0	23.3	6.1	16.4
	224	800	274.0	1023.9	6467.2	6976.3	6663.2	1541.0	11073.8	34019	0.8	3.0	19.0	20.5	19.6	4.5	32.6
		600	215.4	1500.2	8163.5	8032.3	8297.6	2259.2	6912.0	35380	0.6	4.2	23.1	22.7	23.5	6.4	19.5
		700	204.0	1336.4	7112.4	8056.2	7451.1	2014.8	8298.1	34473	0.6	3.9	20.6	23.4	21.6	5.8	24.1
3	224	600	190.0	1713.8	7652.3	7923.0	8005.2	2409.4	8393.7	36287	0.5	4.7	21.1	21.8	22.1	6.6	23.1
		800	210.5	998.5	5953.7	6751.2	6169.1	1434.4	12502.0	34019	0.6	2.9	17.5	19.8	18.1	4.2	36.7
		700	189.4	1160.1	7090.4	7380.8	7272.2	1747.1	8272.2	33112	0.6	3.5	21.4	22.3	22.0	5.3	25.0
	448	800	318.4	976.3	6698.4	8158.0	6808.7	1526.0	10440.8	34927	0.9	2.8	19.2	23.4	19.5	4.4	29.9
		600	221.8	1383.2	7691.7	7929.9	7958.5	2077.4	7664.1	34927	0.6	4.0	22.0	22.7	22.8	5.9	21.9
		700	244.5	1221.8	7522.8	8038.0	7712.1	1917.8	7816.0	34473	0.7	3.5	21.8	23.3	22.4	5.6	22.7
										Mean	0.8	3.9	20.2	22.4	20.7	5.4	26.6
										SD	0.4	0.8	1.9	1.7	2.1	0.9	6.5
										CV	0.5	0.2	0.1	0.1	0.1	0.2	0.2

Table D.2. Mass of potash collected in different zones of collection device for Vane 2.

Rep	Rate (kg ha^{-1})	Disc Speed (rpm)	Collected Mass (g)							Total Mass Envizio (g)	Mass Percentage by Zone (%)						
			Zone No.														
			1	2	3	4	5	6	7		1	2	3	4	5	6	7
1	224	700	283.2	1668.0	7990.3	10117.2	8541.8	1594.6	4731.6	34927	0.8	4.8	22.9	29.0	24.5	4.6	13.5
		600	198.3	1714.9	8358.6	8672.1	8719.6	1611.5	5651.7	34927	0.6	4.9	23.9	24.8	25.0	4.6	16.2
		800	221.1	1262.0	7686.6	9128.2	8079.2	1209.6	6432.7	34019	0.6	3.7	22.6	26.8	23.7	3.6	18.9
	448	800	249.6	1263.6	7791.3	9700.5	8251.8	1207.3	6009.0	34473	0.7	3.7	22.6	28.1	23.9	3.5	17.4
		600	218.0	1647.9	8443.6	8518.7	8789.3	1460.9	5394.5	34473	0.6	4.8	24.5	24.7	25.5	4.2	15.6
		700	246.0	1455.6	8273.3	9958.6	8659.0	1366.5	4060.5	34019	0.7	4.3	24.3	29.3	25.5	4.0	11.9
2	448	600	168.1	1672.0	9294.9	9339.9	9711.6	1827.8	2912.3	34927	0.5	4.8	26.6	26.7	27.8	5.2	8.3
		800	223.9	1344.8	7793.3	12524.0	8490.1	1304.0	3700.1	35380	0.6	3.8	22.0	35.4	24.0	3.7	10.5
		700	262.9	1385.0	8181.1	10401.7	8983.2	1299.5	3959.6	34473	0.8	4.0	23.7	30.2	26.1	3.8	11.5
	224	800	250.3	1010.2	8218.9	9074.1	8802.8	1157.4	5052.1	33566	0.7	3.0	24.5	27.0	26.2	3.4	15.1
		700	237.1	1504.7	7929.8	9213.0	8404.6	1411.1	5319.1	34019	0.7	4.4	23.3	27.1	24.7	4.1	15.6
		600	256.7	1755.9	8597.4	9536.2	9310.1	1638.6	3831.7	34927	0.7	5.0	24.6	27.3	26.7	4.7	11.0
3	448	800	278.6	1025.0	8595.2	10166.9	9109.4	1038.3	4713.2	34927	0.8	2.9	24.6	29.1	26.1	3.0	13.5
		700	267.4	1158.6	8470.9	9433.8	9363.8	1348.1	5337.6	35380	0.8	3.3	23.9	26.7	26.5	3.8	15.1
		600	225.3	1299.3	9227.3	9263.7	9591.6	1385.0	2573.6	33566	0.7	3.9	27.5	27.6	28.6	4.1	7.7
	224	600	161.8	1374.8	9202.0	9155.9	9850.2	1475.8	3252.5	34473	0.5	4.0	26.7	26.6	28.6	4.3	9.4
		800	421.3	876.1	7934.9	10467.0	8724.1	924.3	4671.7	34019	1.2	2.6	23.3	30.8	25.6	2.7	13.7
		700	260.0	1014.6	8899.5	10393.8	9341.4	1124.8	3438.9	34473	0.8	2.9	25.8	30.2	27.1	3.3	10.0
										Mean	0.7	3.9	24.3	28.2	25.9	3.9	13.1
										SD	0.2	0.8	1.5	2.5	1.5	0.6	3.2
										CV	0.2	0.2	0.1	0.1	0.1	0.2	0.2

Table D.3. Mass of potash collected in different zones of collection device for Vane 3.

Rep	Rate (kg ha^{-1})	Disc Speed (rpm)	Collected Mass (g)							Total Mass Envizio (g)	Mass Percentage by Zone (%)						
			Zone No.														
			1	2	3	4	5	6	7		1	2	3	4	5	6	7
1	224	800	142.3	422.6	8397.7	8562.6	8938.3	502.2	7053.7	34019	0.4	1.2	24.7	25.2	26.3	1.5	20.7
		600	136.5	901.7	9972.1	7895.4	10859	891.8	2909.2	33566	0.4	2.7	29.7	23.5	32.4	2.7	8.7
		700	119.8	795.8	9952.2	8590.9	10589	833.6	5406.6	36287	0.3	2.2	27.4	23.7	29.2	2.3	14.9
	448	700	113	985.6	9636.9	8343.1	10470	954.9	4876.8	35380	0.3	2.8	27.2	23.6	29.6	2.7	13.8
		800	189.5	946.8	8381.1	9874.8	8838.7	795.8	9075.06	38102	0.5	2.5	22.0	25.9	23.2	2.1	23.8
		600	173.9	1554.5	9896.3	8700.3	10546	1535	2067.4	34473	0.5	4.5	28.7	25.2	30.6	4.5	6.0
2	224	600	195.9	1541	9759.1	8656.7	10610	1468.2	3602.5	35834	0.5	4.3	27.2	24.2	29.6	4.1	10.1
		700	142.3	986.5	9180.7	8067.3	9972.7	893.7	6137.0	35380	0.4	2.8	25.9	22.8	28.2	2.5	17.3
		800	339.6	537.1	8632	9061.9	8952.8	589.8	5906.2	34019	1.0	1.6	25.4	26.6	26.3	1.7	17.4
	448	800	236.5	706.6	7656.6	8349.7	8529.8	611.5	8835.9	34927	0.7	2.0	21.9	23.9	24.4	1.8	25.3
		700	190.3	1104.4	10072	9101	9627.6	1014.6	4270.0	35380	0.5	3.1	28.5	25.7	27.2	2.9	12.1
		600	175	1177.4	10073	8417.8	10730	963.4	2482.4	34019	0.5	3.5	29.6	24.7	31.5	2.8	7.3
3	448	800	155.8	900.1	8046.9	8379.6	8530.1	828	8086.1	34927	0.4	2.6	23.0	24.0	24.4	2.4	23.2
		600	158.8	1425	10397	8222.7	11158	1222.4	1436.4	34019	0.5	4.2	30.6	24.2	32.8	3.6	4.2
		700	140.3	981.7	9470.8	7923.2	9753.3	912.1	4384.4	33566	0.4	2.9	28.2	23.6	29.1	2.7	13.1
	224	700	143.9	1080.4	10120	8295.9	10669	958.8	4112.2	35380	0.4	3.1	28.6	23.4	30.2	2.7	11.6
		800	214.5	763.5	8668.6	9361.3	9212.9	722.5	4622.5	33566	0.6	2.3	25.8	27.9	27.4	2.2	13.8
		600	117.7	1560.2	9568	8132.9	10460	1601.7	4393.2	35834	0.3	4.4	26.7	22.7	29.2	4.5	12.3
										Mean	0.5	2.9	26.7	24.5	28.4	2.7	14.2
										SD	0.2	0.9	2.6	1.4	2.7	0.9	6.1
										CV	0.3	0.3	0.1	0.1	0.1	0.3	0.4

Table D.4. Mass of potash collected in different zones of collection device for Vane 4.

Rep	Rate (kg ha^{-1})	Disc Speed rpm	Collected Mass (g)							Total Mass Envizio (g)	Mass Percentage by Zone (%)						
			Zone No.														
			1	2	3	4	5	6	7		1	2	3	4	5	6	7
1	448	700	192.7	1202.7	10177.3	7939.6	10603.0	1024.2	2879.9	34019	0.6	3.5	29.9	23.3	31.2	3.0	8.5
		800	485.9	1012.5	9272.8	9556.0	10166.1	887.9	3091.8	34473	1.4	2.9	26.9	27.7	29.5	2.6	9.0
		600	107.6	1930.2	10349.2	7856.4	11000.9	1762.6	3280.5	36287	0.3	5.3	28.5	21.7	30.3	4.9	9.0
	224	600	174.9	1327.7	10428.3	8513.1	11526.8	1246.0	349.0	33566	0.5	4.0	31.1	25.4	34.3	3.7	1.0
		700	159.5	1150.0	10375.7	8740.7	10960.5	980.0	1653.0	34019	0.5	3.4	30.5	25.7	32.2	2.9	4.9
		800	144.2	1477.0	9545.2	7571.8	9907.8	1220.2	4606.8	34473	0.4	4.3	27.7	22.0	28.7	3.5	13.4
2	224	600	155.2	1393.9	10578.6	8629.4	11389.3	1192.2	1134.4	34473	0.5	4.0	30.7	25.0	33.0	3.5	3.3
		800	145.3	1596.9	9732.4	8736.2	10634.6	1329.6	2751.6	34927	0.4	4.6	27.9	25.0	30.4	3.8	7.9
		700	199.5	1666.3	9758.5	8378.6	10593.4	1452.9	1516.6	33566	0.6	5.0	29.1	25.0	31.6	4.3	4.5
	448	800	169.6	1284.9	9330.4	8929.2	9751.4	1132.2	3875.3	34473	0.5	3.7	27.1	25.9	28.3	3.3	11.2
		700	139.7	1695.9	9970.6	8719.0	10679.4	1516.4	2659.2	35380	0.4	4.8	28.2	24.6	30.2	4.3	7.5
		600	144.3	1498.7	10440.1	7622.5	11398.8	1300.9	2521.3	34927	0.4	4.3	29.9	21.8	32.6	3.7	7.2
3	448	800	126.0	1615.0	10870.0	7495.6	11810.3	1425.9	1130.2	34473	0.4	4.7	31.5	21.7	34.3	4.1	3.3
		600	119.4	1626.9	10895.0	7498.6	11883.9	1400.6	595.0	34019	0.4	4.8	32.0	22.0	34.9	4.1	1.7
		700	112.9	1702.2	10452.2	8436.7	11322.3	1563.3	1337.0	34927	0.3	4.9	29.9	24.2	32.4	4.5	3.8
	224	600	114.4	1911.0	10295.7	7746.7	11320.9	1794.0	1743.9	34927	0.3	5.5	29.5	22.2	32.4	5.1	5.0
		700	157.7	1676.6	9789.0	8250.5	10688.3	1581.5	1875.8	34019	0.5	4.9	28.8	24.3	31.4	4.6	5.5
		800	187.6	1386.1	9339.6	8107.9	10283.7	1207.6	3960.5	34473	0.5	4.0	27.1	23.5	29.8	3.5	11.5
										Mean	0.5	4.4	29.2	23.9	31.5	3.9	6.6
										SD	0.2	0.7	1.6	1.8	1.9	0.7	3.5
										CV	0.5	0.2	0.1	0.1	0.1	0.2	0.5

APPENDIX E: SUMMARIZED DATA TABLES AND FIGURES ALONG WITH INCLUDED STATISTICS.

Table E.1. Overall mean mass material distribution (%) for all four vane shapes at feed rate of 448 kg ha^{-1} in different zones of the collection device at three spinner disc-speeds of 600, 700 and 800 rpm.

Vane	Disc Speed (rpm)	Zone No.				
		2	3	4	5	6
1	600	5.7^{a}	27.8^{c}	30.1^{a}	28.6^{b}	7.8^{a}
2		5.0^{b}	29.5^{b}	29.7^{ab}	30.7^{b}	5.1^{b}
3		4.3^{a}	31.6^{a}	26.4^{bc}	33.8^{a}	3.9^{b}
4		5.1^{a}	32.2^{a}	23.3^{c}	34.8^{a}	4.5^{b}
1	700	4.8^{a}	27.8^{b}	31.8^{a}	28.4^{c}	7.2^{a}
2		4.5^{ab}	27.8^{b}	33.2^{a}	30.1^{bc}	4.5^{b}
3		3.4^{b}	32.3^{a}	28.1^{b}	33.0^{ab}	3.2^{c}
4		4.7^{a}	31.5^{a}	25.9^{b}	33.6^{a}	4.2^{bc}
1	800	4.9^{a}	27.7^{b}	33.0^{ab}	27.8^{c}	6.6^{a}
2		4.1^{a}	27.0^{b}	36.1^{a}	28.9^{bc}	4.0^{b}
3		3.1^{a}	29.6^{ab}	32.7^{ab}	31.8^{ab}	2.7^{b}
4		4.1^{c}	31.2^{a}	27.5^{b}	33.6^{a}	3.6^{b}

Means denoted by the same letter are not significantly different (level of confidence α = 95%) within a column for a particular spinner-disc speed.

Table E.2. Overall mean mass material distribution (%) within in Zones 2 and 6 at feed rate of 224 kg ha^{-1} , along with p-values comparing data within a specific treatment.

Vane	Disc Speed (rpm)	Zone No.		p-value
		2	6	
1	600	5.7	7.8	0.2474
2		5.0	5.1	1.0000
3		4.3	3.9	0.6719
4		5.1	4.5	0.4227
1	700	4.8	7.2	0.1367
2		4.5	4.5	0.8335
3		3.4	3.2	0.2414
4		4.7	4.2	0.4164
1	800	4.9	6.6	0.1413
2		4.1	4.0	0.8335
3		3.1	2.7	0.3187
4		4.1	3.6	0.6807

Table E.3. Overall mean mass material distribution (%) within Zones 3 and 5 at feed rate of 448 kg ha^{-1} along with p-values comparing data within a specific treatment.

Vane	Disc Speed (rpm)	Zone No.		p-value
		3	5	
1	600	27.8	28.6	0.4164
2		29.5	30.7	0.1228
3		31.6	33.8	0.1367
4		32.2	34.8	0.1413
1	700	27.8	28.4	0.4227
2		27.8	30.1	0.1413
3		32.3	33.0	0.6764
4		31.5	33.6	0.2474
1	800	27.7	27.8	0.6764
2		27.0	28.9	0.4227
3		29.6	31.8	0.1413
4		31.2	33.6	0.2474

Table E.4. Average percent material captured by zones when considering only Zones 2 through 6 or zones where controlled distribution occurred at feed rate of 224 kg ha^{-1}.

Vane	Zone	Speed	Tukey Grouping
CHAN	5	600	A
TAP	5	700	A B
TAP	5	600	A B C
ORGM	4	800	A B C D
CHAN	5	700	A B C D E
CHAN	5	800	A B C D E
ORGM	4	700	A B C D E F
TAP	5	800	A B C D E F G
TAP	4	800	A B C D E F G
TAP	3	700	A B C D E F G H
ORG	4	800	B C D E F G H I
CHAN	3	600	B C D E F G H I J
TAP	3	600	C D E F G H I J K
CHAN	3	700	D E F G H I J K L
CHAN	3	800	D E F G H I J K L
ORG	4	700	E F G H I J K L M
TAP	3	800	E F G H I J K L M N
ORGM	5	600	F G H I J K L M N O
ORGM	5	800	G H I J K L M N O P
ORGM	4	600	G H I J K L M N O P Q
ORGM	5	700	H I J K L M N O P Q
ORG	5	600	I J K L M N O P Q R
ORGM	3	600	J K L M N O P Q R
ORG	5	800	K L M N O P Q R
ORG	4	600	K L M N O P Q R
ORG	5	700	L M N O P Q R

ORGM	3	800	M N O P Q R
ORG	3	600	M N O P Q R
ORG	3	800	N O P Q R
ORGM	3	700	O P Q R S
ORG	3	700	P Q R S
TAP	4	700	Q R S
CHAN	4	800	R S
CHAN	4	700	R S
TAP	4	600	R S
CHAN	4	600	S
ORG	6	600	T
ORG	6	700	T U
ORG	6	800	T U V
ORG	2	600	T U V W
ORG	2	700	U V W X
ORGM	2	600	U V W X
ORGM	6	600	U V W X
ORG	2	800	U V W X Y
CHAN	2	800	U V W X Y Z
ORGM	2	700	U V W X Y Z
CHAN	2	700	U V W X Y Z
CHAN	2	600	V W X Y Z
ORGM	6	700	V W X Y Z
CHAN	6	600	V W X Y Z
TAP	2	600	V W X Y Z
TAP	6	600	V W X Y Z
CHAN	6	700	V W X Y Z
CHAN	6	800	V W X Y Z
ORGM	6	800	W X Y Z
ORGM	2	800	W X Y Z
TAP	2	700	X Y Z
TAP	6	700	X Y Z

TAP Z	6	800	Y
TAP Z	2	800	

Table E.5. Average percent material captured by zone when considering only Zones 2 through 6 or zones where controlled distribution occurred at feed rate of 224 kg ha^{-1}.

Vane	Disc Speed (rpm)	Zone No. 2	3	4	5	6
		Average Mass (%)				
1	600	6.0^{tuvw}	28.2^{mnopqr}	$28.6^{klmnopqr}$	$28.9^{ijklmnopqr}$	8.3^{t}
2		5.3^{uvwx}	$28.8^{jklmnopqr}$	$30.1^{ghijklmnopq}$	$30.6^{fghijklmno}$	5.2^{uvwx}
3		4.3^{vwxyz}	$31.2^{cdefghijk}$	26.3^{rs}	34.0^{abc}	4.2^{vwxyz}
4		4.7^{vwxyz}	$31.5^{bcdefghi}$	25.1^{s}	34.5^{a}	4.3^{vwxyz}
1	700	5.4^{uvwx}	27.8^{opqrs}	$30.9^{efghijklm}$	$28.4^{lmnopqr}$	7.5^{tu}
2		4.7^{uvwxyz}	27.8^{opqrs}	33.3^{abcdef}	$29.5^{hijklmnopq}$	4.6^{vwxyz}
3		3.1^{xyz}	$32.2^{abcdefgh}$	27.4^{qrs}	34.3^{ab}	3.0^{xyz}
4		4.7^{vwxyz}	$31.2^{defghijkl}$	26.4^{rs}	33.6	4.2^{vwxyz}
1	800	4.9^{uvwxy}	28.1^{nopqr}	$31.6^{bcdefghi}$	$28.7^{klmnopqr}$	6.7^{tuv}
2		3.7^{wxyz}	28.2^{mnopqr}	33.9^{abcd}	$30.3^{ghijklmnop}$	3.9^{wxyz}
3		2.1^{z}	$30.8^{efghijklmn}$	$32.4^{abcdefg}$	$32.5^{abcdefg}$	2.2^{yz}
4		4.8^{uvwxyz}	$31.1^{defghijkl}$	26.5^{rs}	33.5^{abcde}	4.1^{vwxyz}

Means denoted by the same letter are not significantly different (level of confidence α = 95%).

Table E.6. Impact of increase in spinner disc speed on maximum transverse distance by Vane.

	------------------- Disc Speed (rpm) --------------------		
Vane	600	700	800
1	13.4	15.3	16.4
2	13.3	14.9	16.4
3	13.4	14.1	16.4
4	14.5	14.9	16.4

Table E.7. Summary of the overlap pattern analyses at effective spread widths of 18.3 and 21.3 m for the four vane designs along with skewing.

				18.3-m Spread Width		21.3-m Spread Width	
Vane	Target Rate (kg ha^{-1})	Disc Speed (rpm)	Skewing (%Left/%Right)	Mean Rate (kg ha^{-1})	CV (%)	Mean Rate (kg ha^{-1})	CV (%)
1	224	600	46.7/53.3	263.6	31.4	211.8	45.1
		700	47.0/53.0	262.5	42.1	210.3	29.9
		800	43.3/56.8	252.0	40.9	206.6	40.0
	448	600	46.6/53.4	494.1	30.5	397.3	44.6
		700	45.0/55.0	475.3	45.6	378.5	35.6
		800	46.7/53.3	394.8	41.2	323.1	41.4
2	224	600	48.5/51.5	276.5	26.0	222.5	42.3
		700	46.2/53.8	304.5	47.1	241.1	30.6
		800	44.5/55.5	257.0	38.4	210.2	31.7
	448	600	47.1/52.9	539.7	33.8	431.9	41.2
		700	47.0/53.0	492.9	41.3	387.6	26.4
		800	45.9/54.1	479.6	39.7	391.4	34.5
3	224	600	47.5/52.5	292.6	35.8	236.4	51.3
		700	44.7/55.3	306.0	43.1	243.9	28.5
		800	45.1/54.9	284.3	43.0	228.7	28.1
	448	600	49.2/50.8	544.4	36.5	436.2	50.2
		700	45.1/54.9	559.6	52.5	445.0	36.3
		800	45.9/54.9	521.6	45.6	4109.7	31.4
4	224	600	49.7/50.3	312.4	40.3	250.2	48.0
		700	47.9/52.1	320.7	46.7	255.0	29.4
		800	44.8/55.2	311.3	46.8	254.9	37.7
	448	600	48.3/51.7	583.9	42.6	468.4	51.2
		700	46.1/53.9	569.8	5308	453.5	35.7
		800	45.5/54.5	513.3	52.4	416.0	42.0

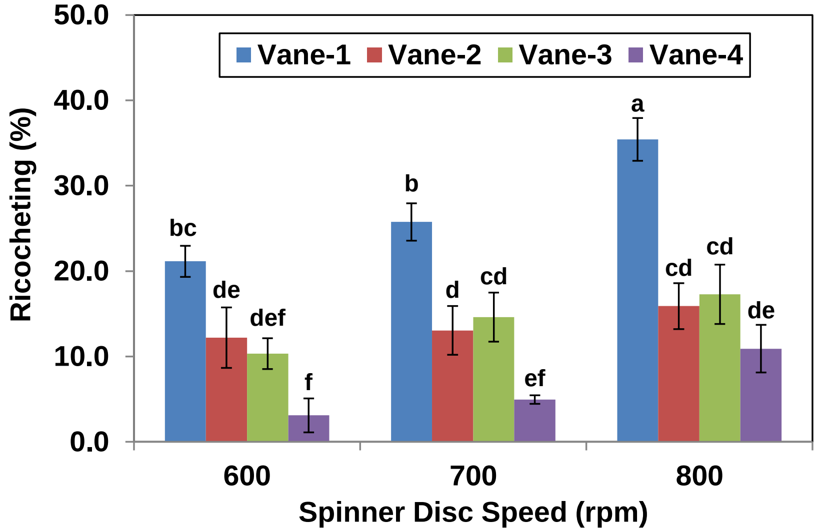
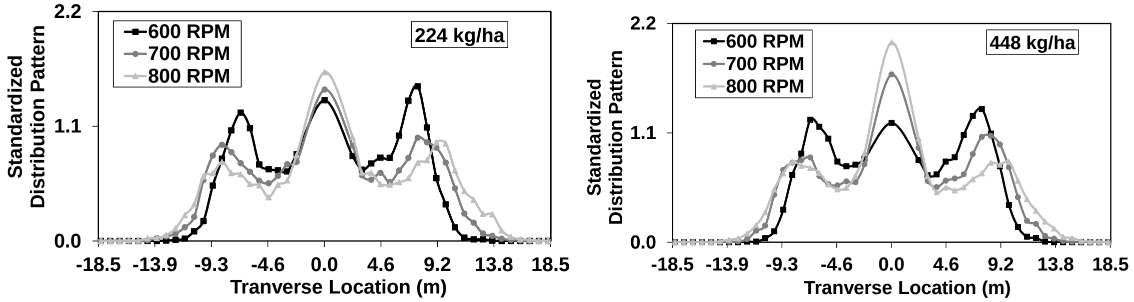
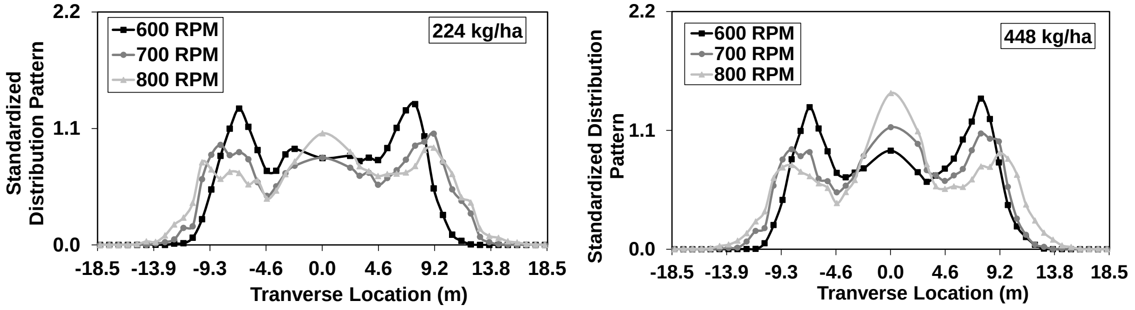


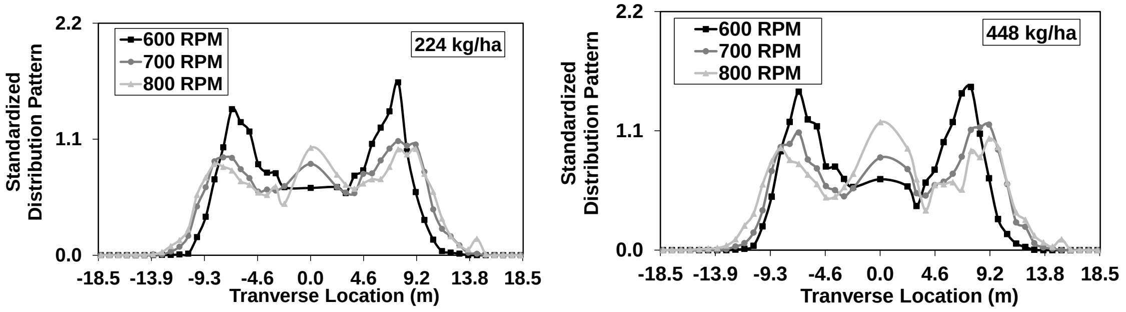
Figure E1. Impact of increase in spinner-disc speed on ricocheting (± 1 SD) for all the four vane shapes at a feed rate of 224 kg ha^{-1}. Means denoted by the same letters are not significantly different (α = 95%).



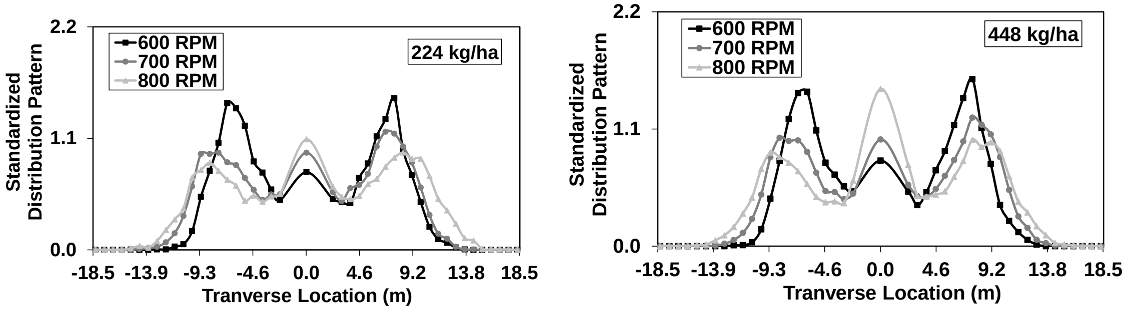
(a) Vane 1



(b) Vane 2



(c) Vane 3



(d) Vane 4

Figure E2. Standardized distribution patterns at 224 kg/h and 448 kg/ha for each vane design. Each curve within the plot represents the mean of three replications. Transverse location represents pan position across the spread width; 0 represents the centreline of the spreader with negative values the left side of the spreader and positive values on the right.

Table E.8. Impact of increase in spinner disc speed on the level of segregation for P_2O_5 and K_2O at all transverse pan locations across the swath.

Pan Location (m)	P_2O_5%			K_2O%		
	600	700	800	600	700	800
-18.3	0.0^{ci}	46.0^{a}	46.0^{a}	0.0^{ci}	0.0^{ci}	0.0^{ci}
-17.5	0.0^{ci}	45.1^{b}	43.0^{f}	0.0^{ci}	0.0^{ci}	4.0^{cd}
-16.8	46.0^{a}	43.7^{e}	40.7^{j}	0.0^{ci}	3.0^{cf}	7.0^{by}
-16.0	46.0^{a}	40.7^{j}	36.8^{q}	0.0^{ci}	6.9^{bz}	12.0^{bp}
-15.2	46.0^{a}	37.1^{p}	33.8^{x}	0.0^{ci}	11.7^{br}	16.0^{bh}
-14.5	40.9^{i}	35.7^{t}	32.2^{ac}	6.8^{ca}	14.0^{bl}	18.0^{bc}
-13.7	37.7^{o}	32.7^{ab}	30.6^{ak}	10.8^{bt}	15.2^{bj}	20.0^{aw}
-13.0	35.8^{s}	31.9^{ad}	29.9^{an}	13.3^{bn}	17.4^{bd}	21.0^{as}
-12.2	34.3^{w}	30.8^{ai}	29.2^{ar}	15.3^{bi}	18.1^{bb}	22.0^{ap}
-11.4	31.6^{af}	29.5^{ap}	27.6^{az}	18.8^{ba}	21.0^{as}	24.0^{ai}
-10.7	31.3^{ah}	28.4^{aw}	26.0^{bk}	19.2^{ay}	22.3^{am}	26.0^{w}
-9.9	30.1^{am}	26.5^{bg}	24.6^{bv}	20.8^{at}	25.5^{z}	28.0^{l}
-9.1	30.2^{al}	25.3^{bq}	24.3^{bx}	21.5^{ar}	27.1^{q}	28.3^{j}
-8.4	28.0^{ay}	24.8^{bu}	23.9^{ca}	23.4^{aj}	27.6^{n}	28.8^{g}
-7.6	25.8^{bm}	24.4^{bw}	24.2^{by}	26.3^{u}	28.2^{k}	28.5^{i}
-6.9	25.2^{br}	24.2^{by}	23.9^{ca}	27.1^{q}	28.5^{i}	28.8^{g}
-6.1	25.1^{bs}	23.9^{ca}	23.7^{cc}	27.3^{p}	28.8^{g}	29.1^{f}
-5.3	24.4^{bw}	24.2^{by}	24.9^{bt}	28.2^{k}	28.5^{i}	27.5^{o}
-4.6	23.5^{cd}	26.7^{bf}	26.2^{bi}	29.4^{d}	24.8^{ad}	25.9^{x}
-3.8	23.3^{ce}	28.0^{ay}	25.7^{bn}	29.7^{c}	24.3^{ag}	26.5^{t}
-3.0	25.9^{bl}	28.6^{au}	26.2^{bi}	26.3^{u}	22.8^{al}	25.8^{y}
-2.3	26.7^{bf}	28.5^{av}	27.5^{ba}	25.2^{aa}	22.8^{al}	24.1^{ah}
0.0	29.1^{as}	29.4^{aq}	29.0^{at}	22.0^{ap}	21.6^{aq}	22.2^{an}
2.3	27.5^{ba}	27.1^{bc}	27.4^{bb}	24.4^{af}	24.6^{ae}	24.4^{af}
3.0	25.6^{bo}	26.1^{bj}	26.9^{bd}	26.6^{s}	26.0^{w}	24.9^{ac}
3.8	26.0^{bk}	25.9^{bl}	26.4^{bh}	26.1^{v}	26.3^{u}	25.5^{z}
4.6	24.6^{bv}	24.1^{bz}	24.8^{bu}	27.9^{m}	28.0^{l}	27.6^{n}
5.3	24.4^{bw}	23.7^{cc}	24.6^{bv}	28.2^{k}	29.2^{e}	27.9^{m}
6.1	23.8^{cb}	23.0^{cg}	24.4^{bw}	28.6^{h}	30.0^{b}	28.2^{k}
6.9	23.9^{ca}	22.8^{ch}	24.2^{by}	28.8^{g}	30.3^{a}	28.5^{i}
7.6	24.3^{bx}	23.2^{cf}	24.4^{bw}	28.3^{j}	29.7^{c}	28.3^{j}
8.4	24.6^{bv}	27.1^{bc}	24.6^{bv}	28.0^{l}	24.6^{ae}	27.9^{m}
9.1	29.1^{as}	29.8^{ao}	25.5^{bp}	22.1^{ao}	20.6^{au}	26.7^{r}
9.9	31.5^{ag}	30.6^{ak}	25.5^{bp}	18.9^{az}	20.1^{av}	26.7^{r}
10.7	33.5^{y}	32.2^{ad}	26.8^{be}	16.2^{bg}	18.0^{bc}	25.1^{ab}
11.4	34.9^{v}	33.4^{z}	28.3^{ax}	14.5^{bk}	16.5^{bf}	23.1^{ak}
12.2	37.8^{m}	36.4^{r}	29.4^{aq}	10.7^{bu}	12.8^{bo}	21.5^{ar}
13.0	40.2^{l}	37.4^{p}	30.7^{aj}	7.7^{bw}	11.8^{bq}	19.9^{ax}
13.7	40.3^{k}	40.3^{k}	33.1^{aa}	6.2^{cb}	7.2^{bx}	16.9^{be}
14.5	42.0^{g}	44.6^{c}	35.6^{u}	3.8^{ce}	1.8^{ch}	13.7^{bm}
15.2	46.0^{a}	46.0^{a}	37.4^{p}	0.0^{ci}	0.0^{ci}	11.2^{bs}
16.0	46.0^{a}	0.0^{ci}	39.3^{m}	0.0^{ci}	0.0^{ci}	8.7^{bv}
16.8	46.0^{a}	0.0^{ci}	41.9^{h}	0.0^{ci}	0.0^{ci}	5.3^{cc}
17.5	0.0^{ci}	0.0^{ci}	44.2^{d}	0.0^{ci}	0.0^{ci}	2.5^{cg}
18.3	0.0^{ci}	0.0^{ci}	46.0^{a}	0.0^{ci}	0.0^{ci}	0.0^{ci}

Means that do not share a letter are significantly different for P_2O_5 and K_2O separately.

Table E.9. The impact of increase in feed rate on level of segregation represented by p-values on nutrient concentration distribution for P_2O_5 and K_2O at all transverse pan locations across the swath.

Pan Location (m)	P_2O_5 (%)			K_2O (%)		
	224 kg ha^{-1}	448 kg ha^{-1}	p-values	224 kg ha^{-1}	448 kg ha^{-1}	p-values
-18.3	30.7	29.8	0.1765	0.0	0.0	0.0500
-17.5	29.4	30.5	0.9161	1.3	1.2	0.1236
-16.8	28.9	29.4	0.0742	3.3	2.1	0.1595
-16.0	41.2	42.7	0.4019	6.3	6.8	0.9325
-15.2	39.0	39.3	0.8843	9.2	9.7	0.8633
-14.5	36.2	37.3	0.6776	12.9	12.7	0.6253
-13.7	33.7	36.3	0.3431	15.3	14.4	0.4503
-13.0	32.5	35.1	0.2789	17.2	16.1	0.3344
-12.2	31.4	34.4	0.2244	18.5	18.0	0.3595
-11.4	29.6	31.6	0.2883	21.3	21.2	0.3051
-10.7	28.6	29.5	0.5265	22.5	24.3	0.7315
-9.9	27.0	28.1	0.3348	24.8	26.8	0.6236
-9.1	26.6	25.5	0.2717	25.6	29.6	0.3335
-8.4	25.6	24.6	0.1701	26.6	30.9	0.1606
-7.6	24.8	24.3	0.0559	27.7	31.6	0.0530
-6.9	24.4	24.4	0.9110	28.1	31.3	0.8630
-6.1	24.2	25.2	0.5100	28.4	30.2	0.0530
-5.3	24.5	25.4	0.0578	28.1	29.9	0.0542
-4.6	25.5	26.8	0.2763	26.7	28.0	0.0504
-3.8	25.7	27.7	0.4587	26.8	26.9	0.0532
-3.0	26.9	28.5	0.7893	24.9	25.6	0.0522
-2.3	27.6	28.8	0.4571	24.0	25.1	0.0512
0.0	29.2	29.0	0.5677	21.9	23.8	0.0514
2.3	27.3	28.1	0.5789	24.4	26.0	0.0603
3.0	26.2	26.7	0.1688	25.9	28.0	0.2004
3.8	26.1	25.7	0.0555	26.0	29.4	0.0725
4.6	24.5	25.1	0.5487	27.8	30.4	0.0730
5.3	24.2	24.6	0.1033	28.4	31.2	0.1237
6.1	23.7	24.2	0.0701	28.9	31.6	0.1462
6.9	23.6	23.9	0.2466	29.2	32.0	0.2401
7.6	24.0	24.3	0.1436	28.7	31.6	0.1557
8.4	25.4	25.8	0.4523	26.8	29.3	0.4334
9.1	28.1	28.0	0.8561	23.1	26.1	0.7431
9.9	29.2	29.1	0.9241	21.9	24.5	0.9415
10.7	30.8	32.1	0.3637	19.8	21.2	0.6692
11.4	32.2	34.6	0.1557	18.0	16.9	0.1496
12.2	34.5	37.6	0.1542	15.0	12.6	0.1446
13.0	36.1	38.2	0.3239	13.1	11.4	0.2599
13.7	37.9	40.1	0.2783	10.1	8.9	0.3780
14.5	40.7	42.9	0.1830	6.4	5.5	0.2733
15.2	43.1	29.6	0.0920	3.7	3.2	0.2669
16.0	28.4	30.7	0.8342	2.9	2.5	0.0628
16.8	29.3	15.3	0.2070	1.8	1.2	0.0628
17.5	14.7	0.0	0.0620	0.8	0.7	0.0628
18.3	15.3	0.0	0.0628	0.0	0.0	0.0500

APPENDIX F: SAS PROGRAM CODE FOR ZONE ANALYSIS IN CHAPTER 3

F.1. Determination of behavior differences for mass collected in different zones of collection device for individual vanes

```
Data fertilizer;
Input Vane$ Rep Rate Speed Z1 Z2 Z3 Z4 Z5 Z6 Z7;
DATALINES;
ORGM    1    200    700    0.8    4.8    22.9    29.0    24.5    4.6    13.5
ORGM    1    200    600    0.6    4.9    23.9    24.8    25.0    4.6    16.2
ORGM    1    200    800    0.6    3.7    22.6    26.8    23.7    3.6    18.9
ORGM    1    400    800    0.7    3.7    22.6    28.1    23.9    3.5    17.4
ORGM    1    400    600    0.6    4.8    24.5    24.7    25.5    4.2    15.6
ORGM    1    400    700    0.7    4.3    24.3    29.3    25.5    4.0    11.9
ORGM    2    400    600    0.5    4.8    26.6    26.7    27.8    5.2    8.3
ORGM    2    400    800    0.6    3.8    22.0    35.4    24.0    3.7    10.5
ORGM    2    400    700    0.8    4.0    23.7    30.2    26.1    3.8    11.5
ORGM    2    200    800    0.7    3.0    24.5    27.0    26.2    3.4    15.1
ORGM    2    200    700    0.7    4.4    23.3    27.1    24.7    4.1    15.6
ORGM    2    200    600    0.7    5.0    24.6    27.3    26.7    4.7    11.0
ORGM    3    400    800    0.8    2.9    24.6    29.1    26.1    3.0    13.5
ORGM    3    400    700    0.8    3.3    23.9    26.7    26.5    3.8    15.1
ORGM    3    400    600    0.7    3.9    27.5    27.6    28.6    4.1    7.7
ORGM    3    200    600    0.5    4.0    26.7    26.6    28.6    4.3    9.4
ORGM    3    200    800    1.2    2.6    23.3    30.8    25.6    2.7    13.7
ORGM    3    200    700    0.8    2.9    25.8    30.2    27.1    3.3    10.0
ORG     1    400    600    2.5    6.0    21.7    22.0    22.0    6.6    19.2
ORG     1    400    800    0.9    3.7    17.3    20.3    17.0    4.4    36.5
ORG     1    400    700    0.6    3.7    19.2    23.5    19.6    5.3    28.2
ORG     1    200    700    0.7    4.5    19.3    22.6    19.2    5.4    28.2
ORG     1    200    800    0.8    3.4    17.3    20.1    17.2    4.1    37.0
ORG     1    200    600    1.2    5.1    21.9    22.5    22.2    6.3    20.8
ORG     2    400    700    0.7    3.5    21.0    24.2    21.6    5.2    23.7
ORG     2    400    800    0.7    3.1    18.0    21.5    18.3    4.2    34.1
ORG     2    400    600    0.8    3.8    22.6    27.0    23.3    6.1    16.4
ORG     2    200    800    0.8    3.0    19.0    20.5    19.6    4.5    32.6
ORG     2    200    600    0.6    4.2    23.1    22.7    23.5    6.4    19.5
ORG     2    200    700    0.6    3.9    20.6    23.4    21.6    5.8    24.1
ORG     3    200    600    0.5    4.7    21.1    21.8    22.1    6.6    23.1
ORG     3    200    800    0.6    2.9    17.5    19.8    18.1    4.2    36.7
ORG     3    200    700    0.6    3.5    21.4    22.3    22.0    5.3    25.0
ORG     3    400    800    0.9    2.8    19.2    23.4    19.5    4.4    29.9
ORG     3    400    600    0.6    4.0    22.0    22.7    22.8    5.9    21.9
ORG     3    400    700    0.7    3.5    21.8    23.3    22.4    5.6    22.7
CHAN    1    400    700    0.6    3.5    29.9    23.3    31.2    3.0    8.5
CHAN    1    400    800    1.4    2.9    26.9    27.7    29.5    2.6    9.0
CHAN    1    400    600    0.3    5.3    28.5    21.7    30.3    4.9    9.0
```

```
CHAN    1    200    600    0.5    4.0    31.1    25.4    34.3    3.7    1.0
CHAN    1    200    700    0.5    3.4    30.5    25.7    32.2    2.9    4.9
CHAN    1    200    800    0.4    4.3    27.7    22.0    28.7    3.5    13.4
CHAN    2    200    600    0.5    4.0    30.7    25.0    33.0    3.5    3.3
CHAN    2    200    800    0.4    4.6    27.9    25.0    30.4    3.8    7.9
CHAN    2    200    700    0.6    5.0    29.1    25.0    31.6    4.3    4.5
CHAN    2    400    800    0.5    3.7    27.1    25.9    28.3    3.3    11.2
CHAN    2    400    700    0.4    4.8    28.2    24.6    30.2    4.3    7.5
CHAN    2    400    600    0.4    4.3    29.9    21.8    32.6    3.7    7.2
CHAN    3    400    800    0.4    4.7    31.5    21.7    34.3    4.1    3.3
CHAN    3    400    600    0.4    4.8    32.0    22.0    34.9    4.1    1.7
CHAN    3    400    700    0.3    4.9    29.9    24.2    32.4    4.5    3.8
CHAN    3    200    600    0.3    5.5    29.5    22.2    32.4    5.1    5.0
CHAN    3    200    700    0.5    4.9    28.8    24.3    31.4    4.6    5.5
CHAN    3    200    800    0.5    4.0    27.1    23.5    29.8    3.5    11.5
TAP     1    200    800    0.4    1.2    24.7    25.2    26.3    1.5    20.7
TAP     1    200    600    0.4    2.7    29.7    23.5    32.4    2.7    8.7
TAP     1    200    700    0.3    2.2    27.4    23.7    29.2    2.3    14.9
TAP     1    400    700    0.3    2.8    27.2    23.6    29.6    2.7    13.8
TAP     1    400    800    0.5    2.5    22.0    25.9    23.2    2.1    23.8
TAP     1    400    600    0.5    4.5    28.7    25.2    30.6    4.5    6.0
TAP     2    200    600    0.5    4.3    27.2    24.2    29.6    4.1    10.1
TAP     2    200    700    0.4    2.8    25.9    22.8    28.2    2.5    17.3
TAP     2    200    800    1.0    1.6    25.4    26.6    26.3    1.7    17.4
TAP     2    400    800    0.7    2.0    21.9    23.9    24.4    1.8    25.3
TAP     2    400    600    0.5    3.5    29.6    24.7    31.5    2.8    7.3
TAP     3    400    800    0.4    2.6    23.0    24.0    24.4    2.4    23.2
TAP     3    400    700    0.4    2.9    28.2    23.6    29.1    2.7    13.1
TAP     3    200    700    0.4    3.1    28.6    23.4    30.2    2.7    11.6
TAP     3    200    800    0.6    2.3    25.8    27.9    27.4    2.2    13.8
TAP     3    200    600    0.3    4.4    26.7    22.7    29.2    4.5    12.3
;

Proc print data=fertilizer;
run;

Proc sort data = fertilizer out=fertilizerN;
by rate speed;
run;

Proc GLM data = fertilizerN;
Class Vane;
By rate speed;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=Vane;
Means Vane/tukey;
run;
```

```
Proc sort data = fertilizer out=fertilizerN;
by rate;run;

Proc GLM data = fertilizerN;
Class Speed ;
By Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=speed;
Means Speed/tukey;
run;
```

F.2. Determination of the effect of change in feed rate and disc speed on material collected in different zones of collection device

```
Data fertilizer;
Input Vane$ Rep Rate Speed Z1 Z2 Z3 Z4 Z5 Z6 Z7;
DATALINES;
ORGM    1    200    700    0.8    4.8    22.9    29.0    24.5    4.6    13.5
ORGM    1    200    600    0.6    4.9    23.9    24.8    25.0    4.6    16.2
ORGM    1    200    800    0.6    3.7    22.6    26.8    23.7    3.6    18.9
ORGM    1    400    800    0.7    3.7    22.6    28.1    23.9    3.5    17.4
ORGM    1    400    600    0.6    4.8    24.5    24.7    25.5    4.2    15.6
ORGM    1    400    700    0.7    4.3    24.3    29.3    25.5    4.0    11.9
ORGM    2    400    600    0.5    4.8    26.6    26.7    27.8    5.2    8.3
ORGM    2    400    800    0.6    3.8    22.0    35.4    24.0    3.7    10.5
ORGM    2    400    700    0.8    4.0    23.7    30.2    26.1    3.8    11.5
ORGM    2    200    800    0.7    3.0    24.5    27.0    26.2    3.4    15.1
ORGM    2    200    700    0.7    4.4    23.3    27.1    24.7    4.1    15.6
ORGM    2    200    600    0.7    5.0    24.6    27.3    26.7    4.7    11.0
ORGM    3    400    800    0.8    2.9    24.6    29.1    26.1    3.0    13.5
ORGM    3    400    700    0.8    3.3    23.9    26.7    26.5    3.8    15.1
ORGM    3    400    600    0.7    3.9    27.5    27.6    28.6    4.1    7.7
ORGM    3    200    600    0.5    4.0    26.7    26.6    28.6    4.3    9.4
ORGM    3    200    800    1.2    2.6    23.3    30.8    25.6    2.7    13.7
ORGM    3    200    700    0.8    2.9    25.8    30.2    27.1    3.3    10.0
;

Proc print data=fertilizer;
run;


Proc GLM data = fertilizer;
Class Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=Rate;
```

```
Means Rate /tukey;
run;
Proc sort data = fertilizer out=fertilizerN;
by rate;
run;

Proc GLM data = fertilizerN;
Class Speed ;
By Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=speed;
Means Speed/tukey;
run;


Data fertilizer2;
Input Vane$ Rep Rate Speed Z1 Z2 Z3 Z4 Z5 Z6 Z7;
DATALINES;
ORG     1    400    600    2.5    6.0    21.7    22.0    22.0    6.6    19.2
ORG     1    400    800    0.9    3.7    17.3    20.3    17.0    4.4    36.5
ORG     1    400    700    0.6    3.7    19.2    23.5    19.6    5.3    28.2
ORG     1    200    700    0.7    4.5    19.3    22.6    19.2    5.4    28.2
ORG     1    200    800    0.8    3.4    17.3    20.1    17.2    4.1    37.0
ORG     1    200    600    1.2    5.1    21.9    22.5    22.2    6.3    20.8
ORG     2    400    700    0.7    3.5    21.0    24.2    21.6    5.2    23.7
ORG     2    400    800    0.7    3.1    18.0    21.5    18.3    4.2    34.1
ORG     2    400    600    0.8    3.8    22.6    27.0    23.3    6.1    16.4
ORG     2    200    800    0.8    3.0    19.0    20.5    19.6    4.5    32.6
ORG     2    200    600    0.6    4.2    23.1    22.7    23.5    6.4    19.5
ORG     2    200    700    0.6    3.9    20.6    23.4    21.6    5.8    24.1
ORG     3    200    600    0.5    4.7    21.1    21.8    22.1    6.6    23.1
ORG     3    200    800    0.6    2.9    17.5    19.8    18.1    4.2    36.7
ORG     3    200    700    0.6    3.5    21.4    22.3    22.0    5.3    25.0
ORG     3    400    800    0.9    2.8    19.2    23.4    19.5    4.4    29.9
ORG     3    400    600    0.6    4.0    22.0    22.7    22.8    5.9    21.9
ORG     3    400    700    0.7    3.5    21.8    23.3    22.4    5.6    22.7
;

Proc print data=fertilizer2;
run;


Proc GLM data = fertilizer2;
Class Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=Rate;
Means Rate /tukey;
run;
```

```
Proc sort data = fertilizer2 out=fertilizer22;
by rate;
run;

Proc GLM data = fertilizer22;
Class Speed ;
By Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=speed;
Means Speed/tukey;
run;


Data fertilizer3;
Input Vane$ Rep Rate Speed Z1 Z2 Z3 Z4 Z5 Z6 Z7;
DATALINES;
CHAN    1    400    700    0.6    3.5    29.9    23.3    31.2    3.0    8.5
CHAN    1    400    800    1.4    2.9    26.9    27.7    29.5    2.6    9.0
CHAN    1    400    600    0.3    5.3    28.5    21.7    30.3    4.9    9.0
CHAN    1    200    600    0.5    4.0    31.1    25.4    34.3    3.7    1.0
CHAN    1    200    700    0.5    3.4    30.5    25.7    32.2    2.9    4.9
CHAN    1    200    800    0.4    4.3    27.7    22.0    28.7    3.5    13.4
CHAN    2    200    600    0.5    4.0    30.7    25.0    33.0    3.5    3.3
CHAN    2    200    800    0.4    4.6    27.9    25.0    30.4    3.8    7.9
CHAN    2    200    700    0.6    5.0    29.1    25.0    31.6    4.3    4.5
CHAN    2    400    800    0.5    3.7    27.1    25.9    28.3    3.3    11.2
CHAN    2    400    700    0.4    4.8    28.2    24.6    30.2    4.3    7.5
CHAN    2    400    600    0.4    4.3    29.9    21.8    32.6    3.7    7.2
CHAN    3    400    800    0.4    4.7    31.5    21.7    34.3    4.1    3.3
CHAN    3    400    600    0.4    4.8    32.0    22.0    34.9    4.1    1.7
CHAN    3    400    700    0.3    4.9    29.9    24.2    32.4    4.5    3.8
CHAN    3    200    600    0.3    5.5    29.5    22.2    32.4    5.1    5.0
CHAN    3    200    700    0.5    4.9    28.8    24.3    31.4    4.6    5.5
CHAN    3    200    800    0.5    4.0    27.1    23.5    29.8    3.5    11.5
;

Proc print data=fertilizer3;
run;


Proc GLM data = fertilizer3;
Class Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=Rate;
Means Rate /tukey;
run;
```

```
Proc sort data = fertilizer3 out=fertilizer33;
by rate;
run;

Proc GLM data = fertilizer33;
Class Speed ;
By Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=speed;
Means Speed/tukey;
run;



Data fertilizer4;
Input Vane$ Rep Rate Speed Z1 Z2 Z3 Z4 Z5 Z6 Z7;
DATALINES;
TAP   1     200   800   0.4   1.2   24.7  25.2  26.3  1.5   20.7
TAP   1     200   600   0.4   2.7   29.7  23.5  32.4  2.7   8.7
TAP   1     200   700   0.3   2.2   27.4  23.7  29.2  2.3   14.9
TAP   1     400   700   0.3   2.8   27.2  23.6  29.6  2.7   13.8
TAP   1     400   800   0.5   2.5   22.0  25.9  23.2  2.1   23.8
TAP   1     400   600   0.5   4.5   28.7  25.2  30.6  4.5   6.0
TAP   2     200   600   0.5   4.3   27.2  24.2  29.6  4.1   10.1
TAP   2     200   700   0.4   2.8   25.9  22.8  28.2  2.5   17.3
TAP   2     200   800   1.0   1.6   25.4  26.6  26.3  1.7   17.4
TAP   2     400   800   0.7   2.0   21.9  23.9  24.4  1.8   25.3
TAP   2     400   700   0.5   3.1   28.5  25.7  27.2  2.9   12.1
TAP   2     400   600   0.5   3.5   29.6  24.7  31.5  2.8   7.3
TAP   3     400   800   0.4   2.6   23.0  24.0  24.4  2.4   23.2
TAP   3     400   600   0.5   4.2   30.6  24.2  32.8  3.6   4.2
TAP   3     400   700   0.4   2.9   28.2  23.6  29.1  2.7   13.1
TAP   3     200   700   0.4   3.1   28.6  23.4  30.2  2.7   11.6
TAP   3     200   800   0.6   2.3   25.8  27.9  27.4  2.2   13.8
TAP   3     200   600   0.3   4.4   26.7  22.7  29.2  4.5   12.3
;

Proc print data=fertilizer4;
run;


Proc GLM data = fertilizer4;
Class Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=Rate;
Means Rate /tukey;
```

```
run;


Proc sort data = fertilizer4 out=fertilizer44;
by rate;
run;

Proc GLM data = fertilizer44;
Class Speed ;
By Rate;
Model Z1 Z2 Z3 Z4 Z5 Z6 Z7=speed;
Means Speed/tukey;
run;
```

APPENDIX G: STATISTICAL RESULTS

Table G.1. ANOVA results comparing mass collection in different zones of collection device at feed rates of 224 kg ha^{-1} and 600 rpm disc-speed for Vanes 1, 2, 3 and 4.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.25666667	0.08555556	1.94	0.2022
Error	8	0.35333333	0.04416667		
Corrected Total	11	0.61			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	1.48666667	0.49555556	0.91	0.4759
Error	8	4.33333333	0.54166667		
Corrected Total	11	5.82			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	117.7633333	39.2544444	24.48	0.0002
Error	8	12.8266667	1.6033333		
Corrected Total	11	130.59			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	24.22916667	8.07638889	5.88	0.0202
Error	8	10.98	1.3725		
Corrected Total	11	35.20916667			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	190.7366667	63.5788889	32.45	<.0001
Error	8	15.6733333	1.9591667		
Corrected Total	11	206.41			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	12.78916667	4.26305556	9.91	0.0045
Error	8	3.44	0.43		
Corrected Total	11	16.22916667			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	494.9266667	164.9755556	28.34	0.0001
Error	8	46.5733333	5.8216667		
Corrected Total	11	541.5			

Table G.2. ANOVA results comparing mass collection in different zones at feed rate of 224 kg ha^{-1} and 700 rpm disc-speed for Vanes 1, 2, 3 and 4.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.25583333	0.08527778	25.58	0.0002
Error	8	0.02666667	0.00333333		
Corrected Total	11	0.2825			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	5.07666667	1.69222222	2.98	0.0963
Error	8	4.54	0.5675		
Corrected Total	11	9.61666667			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	140.2066667	46.7355556	29.93	0.0001
Error	8	12.4933333	1.5616667		
Corrected Total	11	152.7			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	66.17583333	22.05861111	25.45	0.0002
Error	8	6.93333333	0.86666667		
Corrected Total	11	73.10916667			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	199.1425	66.3808333	47.76	<.0001
Error	8	11.12	1.39		
Corrected Total	11	210.2625			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	13.51	4.50333333	13.21	0.0018
Error	8	2.72666667	0.34083333		
Corrected Total	11	16.23666667			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	659.8491667	219.9497222	41.72	<.0001
Error	8	42.18	5.2725		
Corrected Total	11	702.0291667			

Table G.3. ANOVA results comparing mass collection in different zones at feed rate of 224 kg ha^{-1} and 800 rpm disc-speed for Vanes 1, 2, 3 and 4.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.26	0.08666667	1.62	0.2589
Error	8	0.42666667	0.05333333		
Corrected Total	11	0.68666667			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	10.17	3.39	17.38	0.0007
Error	8	1.56	0.195		
Corrected Total	11	11.73			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	152.2466667	50.7488889	89.43	<.0001
Error	8	4.54	0.5675		
Corrected Total	11	156.7866667			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	113.9666667	37.9888889	16.38	0.0009
Error	8	18.5533333	2.3191667		
Corrected Total	11	132.52			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	207.4491667	69.1497222	64.03	<.0001
Error	8	8.64	1.08		
Corrected Total	11	216.0891667			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	9.76916667	3.25638889	30.53	<.0001
Error	8	0.85333333	0.10666667		
Corrected Total	11	10.6225			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	1033.335833	344.445278	41.76	<.0001
Error	8	65.993333	8.249167		
Corrected Total	11	1099.329167			

Table G.4. ANOVA results comparing mass collection in different zones at feed rate of 448 kg ha^{-1} and 600 rpm disc-speed for Vanes 1, 2, 3 and 4.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	1.52242424	0.50747475	1.61	0.2714
Error	7	2.20666667	0.3152381		
Corrected Total	10	3.72909091			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.79636364	0.26545455	0.41	0.7491
Error	7	4.5	0.64285714		
Corrected Total	10	5.29636364			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	111.5974242	37.1991414	22.12	0.0006
Error	7	11.7716667	1.6816667		
Corrected Total	10	123.3690909			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	31.85075758	10.61691919	3.86	0.0641
Error	7	19.23833333	2.74833333		
Corrected Total	10	51.08909091			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	167.4968182	55.8322727	22.96	0.0005
Error	7	17.025	2.4321429		
Corrected Total	10	184.5218182			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	9.71378788	3.23792929	7.1	0.0157
Error	7	3.19166667	0.45595238		
Corrected Total	10	12.90545455			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	314.5404545	104.8468182	8.78	0.009
Error	7	83.585	11.9407143		
Corrected Total	10	398.1254545			

Table G.5. ANOVA results comparing mass collection in different zones at feed rate of 448 kg ha^{-1} and 700 rpm disc-speed for Vanes 1, 2, 3 and 4.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.29681818	0.09893939	10.66	0.0053
Error	7	0.065	0.00928571		
Corrected Total	10	0.36181818			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	3.02893939	1.00964646	3.97	0.0604
Error	7	1.77833333	0.25404762		
Corrected Total	10	4.80727273			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	129.9690909	43.3230303	49.23	<.0001
Error	7	6.16	0.88		
Corrected Total	10	136.1290909			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	53.66545455	17.88848485	15.77	0.0017
Error	7	7.94	1.13428571		
Corrected Total	10	61.60545455			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	168.6689394	56.2229798	54.52	<.0001
Error	7	7.2183333	1.0311905		
Corrected Total	10	175.8872727			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	8.97636364	2.99212121	14.55	0.0022
Error	7	1.44	0.20571429		
Corrected Total	10	10.41636364			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	520.1634848	173.3878283	32.4	0.0002
Error	7	37.4583333	5.3511905		
Corrected Total	10	557.6218182			

Table G.6. ANOVA results comparing mass collection in different zones in Vane 2 at feed rates of 224 kg ha^{-1} and 448 kg ha^{-1}.

Dependent Variable: Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.00888889	0.00888889	0.35	0.5636
Error	16	0.40888889	0.02555556		
Corrected Total	17	0.41777778			

Dependent Variable: Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.00222222	0.00222222	0	0.9532
Error	16	9.99777778	0.62486111		
Corrected Total	17	10			

Dependent Variable: Z3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.245	0.245	0.1	0.7561
Error	16	39.26444444	2.45402778		
Corrected Total	17	39.50944444			

Dependent Variable: Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	3.7355556	3.7355556	0.58	0.4555
Error	16	102.1822222	6.3863889		
Corrected Total	17	105.9177778			

Dependent Variable: Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.20055556	0.20055556	0.09	0.7741
Error	16	37.66888889	2.35430556		
Corrected Total	17	37.86944444			

Dependent Variable: Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0	0	0	1
Error	16	6.81111111	0.42569444		
Corrected Total	17	6.81111111			

Dependent Variable: Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	7.8672222	7.8672222	0.76	0.3963
Error	16	165.6777778	10.3548611		
Corrected Total	17	173.545			

Table G.7. ANOVA results comparing mass collection in different zones of collection device at feed rates of 224 kg ha^{-1} and 448 kg ha^{-1} in Vane 1.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.22222222	0.22222222	1.11	0.308
Error	16	3.20888889	0.20055556		
Corrected Total	17	3.43111111			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.06722222	0.06722222	0.1	0.762
Error	16	11.31777778	0.70736111		
Corrected Total	17	11.385			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.14222222	0.14222222	0.04	0.85
Error	16	61.20888889	3.82555556		
Corrected Total	17	61.35111111			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	8.26888889	8.26888889	3.17	0.094
Error	16	41.78222222	2.61138889		
Corrected Total	17	50.05111111			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.05555556	0.05555556	0.01	0.915
Error	16	75.60444444	4.72527778		
Corrected Total	17	75.66			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.045	0.045	0.06	0.817
Error	16	12.98	0.81125		
Corrected Total	17	13.025			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	11.52	11.52	0.26	0.618
Error	16	714.5044444	44.6565278		
Corrected Total	17	726.0244444			

Table G.8. ANOVA results comparing mass collection in different zones of collection device at three different spinner disc speeds of 600, 700 and 800 rpm in Vane 1 at feed rate of 224 kg ha^{-1}.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.02888889	0.01444444	0.27	0.772
Error	6	0.32	0.05333333		
Corrected Total	8	0.34888889			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3.69555556	1.84777778	10.53	0.011
Error	6	1.05333333	0.17555556		
Corrected Total	8	4.74888889			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	25.62	12.81	12.81	0.007
Error	6	6	1		
Corrected Total	8	31.62			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	11.96222222	5.98111111	26.78	0.001
Error	6	1.34	0.22333333		
Corrected Total	8	13.30222222			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	28.20222222	14.1011111	9.67	0.013
Error	6	8.74666667	1.45777778		
Corrected Total	8	36.94888889			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	7.08666667	3.54333333	77.78	<.0001
Error	6	0.27333333	0.04555556		
Corrected Total	8	7.36			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	319.4022222	159.701111	34.2	5E-04
Error	6	28.02	4.67		
Corrected Total	8	347.4222222			

Table G.9. ANOVA results comparing mass collection in different zones of collection device at three different spinner disc speeds of 600, 700 and 800 rpm in Vane 1 at feed rate of 448 kg ha^{-1}.

Dependent Variable Zone-1

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	0.6466667	0.32333333	0.88	0.464
Error	6	2.2133333	0.36888889		
Corrected Total	8	2.86			

Dependent Variable Zone-2

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	3.1622222	1.58111111	2.78	0.14
Error	6	3.4066667	0.56777778		
Corrected Total	8	6.5688889			

Dependent Variable Zone-3

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	23.775556	11.8877778	12.27	0.008
Error	6	5.8133333	0.96888889		
Corrected Total	8	29.588889			

Dependent Variable Zone-4

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	8.4866667	4.24333333	1.27	0.346
Error	6	19.993333	3.33222222		
Corrected Total	8	28.48			

Dependent Variable Zone-5

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	30.508889	15.2544444	11.23	0.009
Error	6	8.1466667	1.35777778		
Corrected Total	8	38.655556			

Dependent Variable Zone-6

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	5.2466667	2.62333333	42.16	3E-04
Error	6	0.3733333	0.06222222		
Corrected Total	8	5.62			

Dependent Variable Zone-7

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	312.46889	156.234444	17.16	0.003
Error	6	54.613333	9.1022222		
Corrected Total	8	367.08222			

Table G.10. ANOVA results comparing mass collection in different zones of collection device at three different spinner disc speeds of 600, 700 and 800 rpm in Vane 2 at feed rate of 224 kg ha^{-1}.

Dependent Variable: Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.00888889	0.00888889	0.35	0.564
Error	16	0.40888889	0.02555556		
Corrected Total	17	0.41777778			

Dependent Variable: Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.00222222	0.00222222	0.00	0.953
Error	16	9.99777778	0.62486111		
Corrected Total	17	10			

Dependent Variable: Z3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.245	0.245	0.10	0.756
Error	16	39.26444444	2.45402778		
Corrected Total	17	39.50944444			

Dependent Variable: Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	3.7355556	3.7355556	0.58	0.456
Error	16	102.1822222	6.3863889		
Corrected Total	17	105.9177778			

Dependent Variable: Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.20055556	0.20055556	0.09	0.774
Error	16	37.66888889	2.35430556		
Corrected Total	17	37.86944444			

Dependent Variable: Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0	0.00000000	0.00	1
Error	16	6.81111111	0.42569444		
Corrected Total	17	6.81111111			

Dependent Variable: Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	7.8672222	7.8672222	0.76	0.396
Error	16	165.6777778	10.3548611		
Corrected Total	17	173.545			

Table G.11. ANOVA results comparing mass collection in different zones of collection device at three different spinner disc speeds of 600, 700 and 800 rpm in Vane 2 at feed rate of 448 kg ha^{-1}.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.04222222	0.02111111	2.71	0.1447
Error	6	0.04666667	0.00777778		
Corrected Total	8	0.08888889			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.62888889	0.81444444	3.15	0.1163
Error	6	1.55333333	0.25888889		
Corrected Total	8	3.18222222			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	15.61555556	7.80777778	5.43	0.0451
Error	6	8.63333333	1.43888889		
Corrected Total	8	24.24888889			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	30.86222222	15.43111111	2.19	0.1935
Error	6	42.34	7.05666667		
Corrected Total	8	73.20222222			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	10.40666667	5.20333333	3.56	0.0957
Error	6	8.77333333	1.46222222		
Corrected Total	8	19.18			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.82888889	0.91444444	5.34	0.0465
Error	6	1.02666667	0.17111111		
Corrected Total	8	2.85555556			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	16.89555556	8.44777778	0.72	0.5246
Error	6	70.41333333	11.73555556		
Corrected Total	8	87.30888889			

Table G.12. ANOVA results comparing mass collection in different zones of collection device at feed rates of 224 kg ha^{-1} and 448 kg ha^{-1} in Vane 3.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0	0.00000000	0.00	1
Error	16	0.47111111	0.02944444		
Corrected Total	17	0.47111111			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.68055556	0.68055556	0.74	0.403
Error	16	14.75555556	0.92222222		
Corrected Total	17	15.43611111			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.1605556	0.1605556	0.02	0.882
Error	16	112.4955556	7.0309722		
Corrected Total	17	112.6561111			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.03555556	0.03555556	0.02	0.895
Error	16	31.74222222	1.98388889		
Corrected Total	17	31.77777778			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	2	2.00000000	0.25	0.621
Error	16	126.0311111	7.8769444		
Corrected Total	17	128.0311111			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.09388889	0.09388889	0.11	0.741
Error	16	13.28888889	0.83055556		
Corrected Total	17	13.38277778			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.2222222	0.2222222	0.01	0.941
Error	16	636.9577778	39.8098611		
Corrected Total	17	637.18			

Table G.13. ANOVA results comparing mass collection in different zones of collection device at three different spinner disc speeds of 600, 700 and 800 rpm in Vane 3 at feed rate of 224 kg ha^{-1}.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.16222222	0.08111111	2.28	0.183
Error	6	0.21333333	0.03555556		
Corrected Total	8	0.37555556			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	6.62	3.31000000	6.94	0.028
Error	6	2.86	0.47666667		
Corrected Total	8	9.48			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	10.90888889	5.45444444	3.46	0.1
Error	6	9.44666667	1.57444444		
Corrected Total	8	20.35555556			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	20.30888889	10.1544444	11.73	0.008
Error	6	5.19333333	0.86555556		
Corrected Total	8	25.50222222			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	21.79555556	10.8977778	7.36	0.024
Error	6	8.88666667	1.48111111		
Corrected Total	8	30.68222222			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	5.96222222	2.98111111	8.41	0.018
Error	6	2.12666667	0.35444444		
Corrected Total	8	8.08888889			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	73.2822222	36.6411111	4.7	0.059
Error	6	46.7866667	7.7977778		
Corrected Total	8	120.0688889			

Table G.14. ANOVA results comparing mass collection in different zones of collection device at three different spinner disc speeds of 600, 700 and 800 rpm in Vane 3 at feed rate of 448 kg ha^{-1}.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.02888889	0.01444444	1.3	0.34
Error	6	0.06666667	0.01111111		
Corrected Total	8	0.09555556			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	4.49555556	2.24777778	17.29	0.003
Error	6	0.78	0.13000000		
Corrected Total	8	5.27555556			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	88.66666667	44.3333333	76.58	<.0001
Error	6	3.47333333	0.57888889		
Corrected Total	8	92.14			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.26	0.13000000	0.13	0.88
Error	6	5.98	0.99666667		
Corrected Total	8	6.24			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	88.73555556	44.3677778	40.25	3E-04
Error	6	6.61333333	1.10222222		
Corrected Total	8	95.34888889			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3.54666667	1.77333333	6.44	0.032
Error	6	1.65333333	0.27555556		
Corrected Total	8	5.2			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	508.2422222	254.121111	176.34	<.0001
Error	6	8.6466667	1.4411111		
Corrected Total	8	516.8888889			

Table G.15. ANOVA results comparing mass collection in different zones of collection device at feed rates of 224 kg ha^{-1} and 448 kg ha^{-1} in Vane 4.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.01388889	0.01388889	0.22	0.643
Error	16	0.99555556	0.06222222		
Corrected Total	17	1.00944444			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.03555556	0.03555556	0.07	0.797
Error	16	8.32444444	0.52027778		
Corrected Total	17	8.36			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.125	0.1250000	0.05	0.83
Error	16	41.79777778	2.61236111		
Corrected Total	17	41.92277778			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1.50222222	1.50222222	0.47	0.504
Error	16	51.48222222	3.21763889		
Corrected Total	17	52.98444444			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.00055556	0.00055556	0	0.991
Error	16	62.21555556	3.88847222		
Corrected Total	17	62.21611111			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.00888889	0.00888889	0.02	0.896
Error	16	8.07555556	0.50472222		
Corrected Total	17	8.08444444			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.98	0.98	0.08	0.785
Error	16	204.46	12.77875		
Corrected Total	17	205.44			

Table G.16. ANOVA results comparing mass collection in different zones of collection device at three different spinner disc speeds of 600, 700 and 800 rpm in Vane 4 at feed rate of 224 kg ha^{-1}.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.02	0.01000000	1.5	0.296
Error	6	0.04	0.00666667		
Corrected Total	8	0.06			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.06222222	0.03111111	0.06	0.945
Error	6	3.28666667	0.54777778		
Corrected Total	8	3.34888889			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	12.76222222	6.38111111	11.33	0.009
Error	6	3.38	0.56333333		
Corrected Total	8	16.14222222			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3.38	1.69000000	0.88	0.463
Error	6	11.56	1.92666667		
Corrected Total	8	14.94			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	19.62	9.81	15.82	0.004
Error	6	3.72	0.62		
Corrected Total	8	23.34			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.38888889	0.19444444	0.36	0.711
Error	6	3.22666667	0.53777778		
Corrected Total	8	3.61555556			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	100.4466667	50.2233333	12.47	0.007
Error	6	24.1733333	4.0288889		
Corrected Total	8	124.62			

Table G.17. ANOVA results comparing mass collection in different zones of collection device at three different spinner disc speeds of 600, 700 and 800 rpm in Vane 4 at feed rate of 448 kg ha^{-1}.

Dependent Variable Zone-1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.27555556	0.13777778	1.25	0.351
Error	6	0.66	0.11000000		
Corrected Total	8	0.93555556			

Dependent Variable Zone-2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.62888889	0.81444444	1.46	0.304
Error	6	3.34666667	0.55777778		
Corrected Total	8	4.97555556			

Dependent Variable Zone-3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	4.00222222	2.00111111	0.55	0.601
Error	6	21.65333333	3.60888889		
Corrected Total	8	25.65555556			

Dependent Variable Zone-4

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	16.64888889	8.32444444	2.51	0.161
Error	6	19.89333333	3.31555556		
Corrected Total	8	36.54222222			

Dependent Variable Zone-5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	5.70888889	2.85444444	0.52	0.621
Error	6	33.16666667	5.52777778		
Corrected Total	8	38.87555556			

Dependent Variable Zone-6

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.26	0.63000000	1.18	0.369
Error	6	3.2	0.53333333		
Corrected Total	8	4.46			

Dependent Variable Zone-7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	5.40666667	2.70333333	0.22	0.81
Error	6	74.43333333	12.4055556		
Corrected Total	8	79.84			