CHARACTERIZING WATER HOLDING CAPACITY AND TOTAL SOLIDS OF MANURE-BEDDING MIXTURES

BY

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THESIS

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ABSTRACT

Beef producers in the Midwestern United States, driven by environmental regulations, have shown an increased interest in solid manure bedded-pack systems (BPS). BPSs can be an economically and environmentally sound alternative for animal housing, and an efficient manure management alternative for beef production systems, as manure is stored and handled as a solid and eliminates the need for runoff control. Bedding materials are used to absorb excess moisture, improve animal comfort and reduce negative environmental impacts from these livestock facilities. Various biomass types can be used as potential bedding material, such as corn stover, wheat straw and soybean stover. When choosing a bedding material, a number of factors must be considered. Initial moisture content and particle size distribution play an important role in selecting a media for bedding. However, the most important design criteria to consider is the water holding capacity (WHC) of the material and the total solids (TS) of the manure-bedding mixture at saturation. WHC is the moisture a material can retain at the point of saturation.

The main objective of this experimental study was to characterize properties of manure-bedding mixtures that might be found in BPS. These property characterizations included evaluating the impact of several bedding materials and manure TS mixtures on WHC. Seven organic bedding materials were evaluated (corn cobs, corn stover, pine shavings, switchgrass, miscanthus, wheat straw, and soybean stover) and they were characterized for their particle size distribution, bulk density and initial total solids. The first goal of this project was to develop a Standard Operating Procedure (SOP) for measuring WHC with manure addition and the minimum time needed to reach that value. Furthermore, the effect on bedding WHC when beef manure is used in place of water for substrate was determined. To meet this objective, the WHC was evaluated using beef manure at 5 TS levels total solids contents (0%, 4%, 8%, 12% and 16% TS).

An SOP for measuring WHC with manure addition was developed, based on a standard method for non-manure systems in literature. The results of this study, WHC increased

significantly with manure addition. Furthermore, the outcomes of this work indicated that, for the majority of the bedding materials tested, high TS manure slurry (12% or 16%) resulted in lower WHC than did 4% and 8% TS slurry, but all are substantially greater than the baseline WHC without manure slurry addition.

All bedding materials WHC_n ranged from 2.4 to 8.8 g H_2O (g of dry mixture)$^{-1}$. These values were for soybean stover at 16% manure TS and corn stover at 4% manure TS, respectively. If using corn stover and wheat straw the total bedding required per animal per day ranged from 0.6 to 6.6 kg. Compared to current bedding mass recommendations in Illinois the amount of bedding suggested for use in BPS was up to 90% lower, while the total manure-bedding mixture storage volume were greater or lower, depending on the bedding materials bulk density.

To my family and my friends…

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LIST OF FREQUENTLY USED SYMBOLS AND ABBREVIATIONS

Symbols:	*Description*
AFO	Animal Feeding Operation
BPS	Bedded-Pack System
CAFO	Concentrated Animal Feeding Operation
M	Mass
MC	Moisture Content
TS	Total Solids
V	Volume
WHC	Water Holding Capacity
ρ	Bulk Density

Subscripts	*Description*
ab	absorbed by bedding
b	bedding
bp	bed pack
db	dry basis
dm	dry matter
m	manure
mix	mixture
n	normalized
T	total
w	water
wb	wet basis

CHAPTER 1. INTRODUCTION

1.1 Justification

The United States is the world's largest producer of beef for domestic and export use, with the world's largest fed-cattle industry. All cattle and calves in the United States as of 2012 totaled approximately 90 million head, from which 29.0 million were beef cattle as reported from the United States Department of Agriculture (USDA-NASS, 2012). In terms of economic impact, the US beef industry is a $3.5 billion industry.

The Illinois cattle feeding industry remains significant to the state’s economy. According to the 2011 Facts about Illinois Agriculture from the Illinois State Department of Agriculture, Illinois' 76,000 farms cover more than 28 million acres - nearly 80 percent of the state's total land area. There are over 30,000 livestock farms in the state of Illinois of which approximately 23 percent have beef cattle. The 2012 Census of Agriculture (USDA-NASS, 2012) reported that thee are 2,183 beef cattle feedlots in Illinois. Compared to 2007, the total number of feedlots has declined by almost 21%. However, there has been a significant expansion in the number of feedlots housing over 200 head. While the total number of Illinois feedlots has declined the number of animals and value of cattle being fed in the state have increased (USDA-NASS, 2012). The industry directly provides 0.35% to the Illinois economy and 0.23% of the employment (Goldsmith and Idris, 2001).

At the same time that the cattle feeding sector is experiencing growth, there is increasing concern related to agricultural environment practices, including ground and surface water quality impairment due to run-off from open feedlots and air quality concerns related to odor, dust and pests. Specifically, potential air and water pollution from Confined Animal Feeding Operations (CAFOs) have alerted society and regulators towards alternative approaches for managing manure (Bickert, 2003; Randall et al., 2006; Changirath et al., 2011). All animal-feeding operations (AFOs), regardless of design or size, should implement practices and designs to prevent discharges and to utilize manure nutrients efficiently. Manure management is a concern to the agricultural community, but also a societal issue. In response to these concerns, regulatory agencies such as the US and Illinois Environmental Protection Agencies, and the Illinois Department of Agriculture, have increased enforcement of existing laws.

Beef cattle housing systems have a substantial impact on the overall health and welfare of the animals and financially affect the industry. In the Midwestern U.S., beef cattle housing systems have shifted from pasture-based to indoor housing with restricted outdoor access (Barberg et al., 2007a).

Recently, there is an increased interest in solid manure bedded pack barns. Bedded-pack systems (BPS) are an environmental and economical alternative for housing, as well as an efficient animal manure system. Bedded pack systems have significant implications for herd health as well as the environment especially surface water quality. The dairy industry has been using bed pack systems, which were developed as an alternative housing system that appear to offer excellent cow comfort (Endres and Janni 2008, (Endres and Janni 2008; Bewley and Taraba, 2009; Bewley, Taraba and Day, 2013) although managed so as to compost the bedded pack. The main reasons mentioned by livestock producers for building this type of housing system were for improved cow well-being, cow longevity, and ease of completing daily chores (Barberg et al., 2007a).

BPS use bedding materials to absorb excess moisture, to improve animal comfort and reduce adverse environmental impacts from the livestock facilities. Bedding can be a costly component of the BPS. The cost and availability of bedding fluctuate and good consistently available bedding might be hard to find and is often expensive.

There are a variety of organic and inert materials that are used as bedding in the BPS. In the Midwest, corn stover, straw, soybean stover, and wood chips are most commonly used (South Dakota NRCS, 2011). When selecting a bedding material, producers must consider a number of factors such as the level of absorbency, water retention and evaporation rate, carbon content, physical structure and integrity, effects on animal health, handling systems, availability of supply, and cost (Hill, 2000a). However, the most important factor for design criteria to consider is the water absorbance capacity or water holding capacity (WHC) of the bedding material.

WCH is the amount of moisture a material can retain at the point of saturation. The WHC of any material varies due to the degree of grinding, which alters the particle size and surface area (Spiehs et al., 2013). It might also differ due to differences in initial moisture content. A few studies have reported the WHC of various bedding materials (Spiehs et al., 2011; Spiehs et al., 2013; Kuan and Liong, 2008). Spiehs et al. (2013) found that finely ground particles absorbed significantly more water than coarse and medium ground particles of the same bedding material.

However, there are no known studies that report WHC of bedding materials when mixed with manure. It is unlikely that significant manure (feces and urine) addition to bedding will result in the same WHC compared with using water. Without knowing absorption capacity characteristics of manure-bedding mixtures, BPSs are likely being sized incorrectly leading to under or oversized facilities (Pepple and Gates, 2013).

1.2 Objectives

The purpose of this thesis was to determine the crucial design criteria for deep-bedded beef cattle facilities and to characterize the properties of various biomass types used as bedding materials for deep-bedded barns and manure mixtures. These property characterizations include evaluating the WHC of these bedding materials and manure mixtures.

Laboratory analysis of seven potential bedding materials, namely ground corn cobs, corn stover, pine shavings, switchgrass, miscanthus, wheat straw and soybean stover was done. These bedding materials were characterized for their particle size distribution (coarse, medium, fine), bulk density, and initial moisture content. The effects on manure-bedding mixture WHC for varying manure total solids contents were evaluated.

The main objective of this research was to evaluate the WHC of various bedding materials when manure is added. The first task of this study was to develop a Standard Operating Procedure (SOP) for measuring the WHC of bedding materials with manure addition, based on standards for water-based methods. To determine the WHC of various biomass with manure addition, WHC was evaluated using beef manure with total solids contents of approximately 4%, 8%, 12% and 16%. Furthermore, a comparison to the baseline WHC (0% TS) was done. The last, but not least, objective was to determine the design implications of this research for BPS. Given the information from this research work, it is possible to more accurately determine the design criteria for a BPS. Answers can be given to questions such as what is the optimal type of bedding material and how much by mass of bedding is required in a BPS in Illinois. Conclusions about the total storage volume required for the manure-bedding mixture are included. Essentially, the above will have key implications on livestock production.

1.3 Organization of the Thesis

This chapter (Chapter 1) provides an overview of the research study and objectives, with each following chapter supporting these objectives. Chapter 2 presents a literature review covering the environmental concerns and regulations related to manure management from feedlots, an overview of the different types of beef feedlots and the manure management practices followed. There is also information given about bedded pack barns, bedding materials and manure. Chapter 3 is the materials and methods section, describing the bedding material selection and processing, as well as the experimental procedures used for the initial characterization of the bedding. This includes testing for initial total solids and moisture content within the bedding, its particle size distribution and the baseline water holding capacity. Additionally, the chapter includes information about the manure used in the experiments and its processing. Finally, the chapter documents the first and basic approach of the SOP developed for the experiments to determine the manure bedding mixture WHC. Additional minor modifications on the previously developed SOP were introduced. The final SOP that was developed in the study is provided in Appendix B. WHC for seven different bedding materials (corn cobs, corn stover, pine shavings, switchgrass, miscanthus, wheat straw and soybean stover) at 0, 4%, 8%, 12% and 16% TS manure addition were evaluated. The following chapter, Chapter 4 includes the results for the initial bedding characterization, the different bedding materials and manure total solids WHCs. Comparison between the WHCs of the various bedding materials and manure total solids and the percent difference from their baseline WHC is presented. A discussion related to the implications of the research and the limitations existing are discussed. Finally, the determination of the crucial design criteria for deep-bedded beef cattle facilities using the results from this research is done. Chapter 5 is the summary and conclusions section, summarizing the most important conclusions of this research drawn and recommendations for future work are incorporated.

CHAPTER 2. LITERATURE REVIEW

To aid in the justifying the need for this research study, this literature review provides an overview of (1) the environmental concerns and regulations related to manure management from livestock facilities, (2) a description of different beef feedlot systems and manure management practices, (3) bedded pack barns, (4) bedding, (5) manure, and (6) the current design criteria associated with the manure storage requirements in BPS.

2.1 Environmental Concerns for Livestock Facilities

Manure from beef feedlots is a valuable source of nutrients for crops and can improve soil productivity (MWPS-18, 2000). It is an excellent potential source of macronutrients (nitrogen (N), phosphorus (P), and potassium (K)), and micronutrients as well as a source of organic matter when added to soils. Nevertheless, water and air can be contaminated because of the manure that is produced by beef cattle. Surface water and groundwater can potentially be polluted with excess nitrates, phosphorus, salts, microorganisms, and pathogens. Production of greenhouse gasses (GHG) from the feedlots is another factor to consider when managing animal manure (Eghball and Power, 1990).

Today, manure management is a challenge. It is no longer just of concern to the agricultural community, but it is also a social issue. It is expensive to handle manure from feedlots and the procedures must meet many requirements, such as to provide environmental protection and allow maximum utilization of manure nutrient use in crop production. Manure handling characteristics alter as consistency changes from liquid to solid. There are several different manure management systems – (lagoon) liquid systems, slurry systems and solid systems (MWPS-18, 2000).

Due to environmental regulations, livestock producers throughout the United States face the challenge to find manure management strategies and technologies that meet these regulations but at the same time are economically feasible (Copeland, 2006).

2.2 Federal and State Environmental Regulations

The U.S. federal Clean Water Act (CWA) regulates CAFOs. Any beef feeding operation with a total capacity of 1,000 head or more is considered a CAFO under the CWA. CAFOs are defined not only by the size of the operation, but also by the combination of the size and the pollutants discharge conditions that could potentially contaminate the United States water. For instance, a site with 300 head or more that releases pollutants through a man-made drainage system to U.S. surface water is also considered a CAFO (Euken et al., 2015), and must obtain a National Pollutant Discharge Elimination System (NDPES) permit. Other requirements include the installation of approved runoff control measures and the implementation of a Nutrient Management Plan (NMP) to handle manure and wastewater.

New rules became effective for Illinois EPA's regulation of CAFOs in Illinois in August 2014. In addition to the federal CAFO rules, the Illinois Department of Agriculture establishes specific requirements regarding the registration and the notification of intent to construct new facilities, setbacks for construction distances, livestock manager training certification, lagoon construction certification, waste management plans and reporting of waste release (LMFA, 1996). The requirements for the design, construction and operation of livestock and waste-handling facilities, as well as the criteria for their siting are currently included in the Illinois Livestock Management Facilities Act (LMFA) and its applicable regulations such as the Notice of Intent to Construct for New Facilities (NOITC) (LMFA, 1996).

2.3 Beef Cattle Feeding Facilities: Lot-based and Building-based

There is a broad range of feedlot facility types in the state: open lots with windbreaks and with or without shed, deep-bedded confinement buildings and slatted floor (deep pit) confinement buildings. Within each of these systems, design and layout can vary considerably.

2.3.1 Open Lot with Windbreak

In the open lot systems (Figure 2.1), cattle are fed in an earthen or concrete open lot with no shed. There is usually on the north and west side of the lot a windbreak fence or trees to provide protection against prevailing winds during the winter. A minimum of 14 m^2 (150 sq. ft.) and 5.5 m^2 (60 sq. ft.) of space are provided per head in open earthen lots with windbreak and in open lots with a concrete surface, respectively.

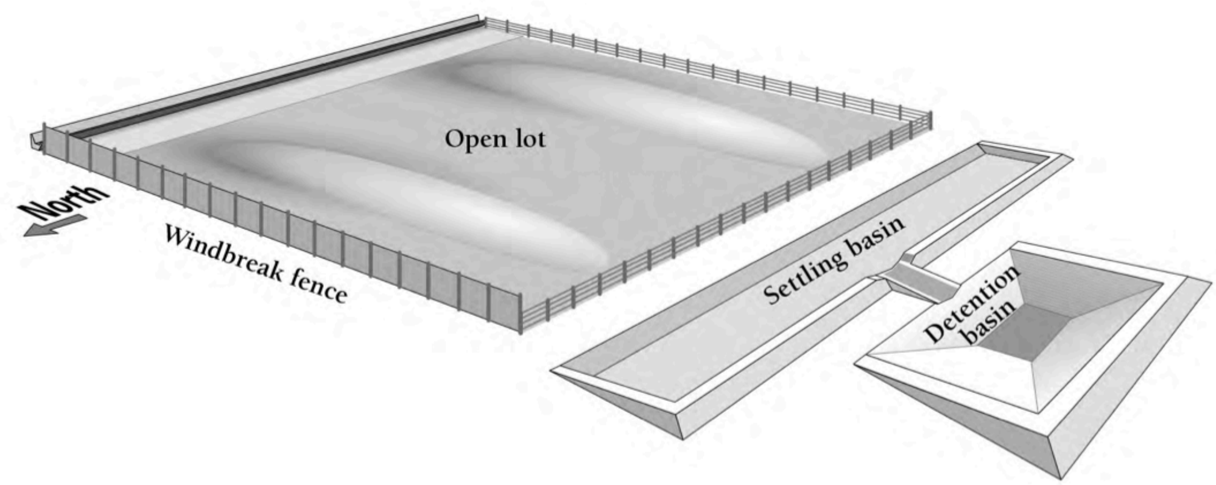

Figure 2.1 Earthen open lot with windbreak (Euken et al., 2015).

2.3.2 Open Lot with Shed

The open lot with shed system (Figure 2.2) is an earthen or concrete open lot with shed. In the case of an earthen open lot 2.5 m^2 (25 sq. ft.) per head are allowed under the shed, with additional 11.5 m^2 (125 sq. ft.) per head at the earthen outside lot. Manure management practices are similar to the open lot with windbreak. Because cattle density in the concrete lot with shed is greater than in the earthen lot, pens are scraped more often, usually weekly. For all sizes of open lots, a solids settling alley is required to allow the solids to settle from pen runoff. These facilities should be located distant from occupied residences, provide enough room to allow for runoff controls, adequate drainage from the surface and at the same time prevent a discharge to United States surface waters.

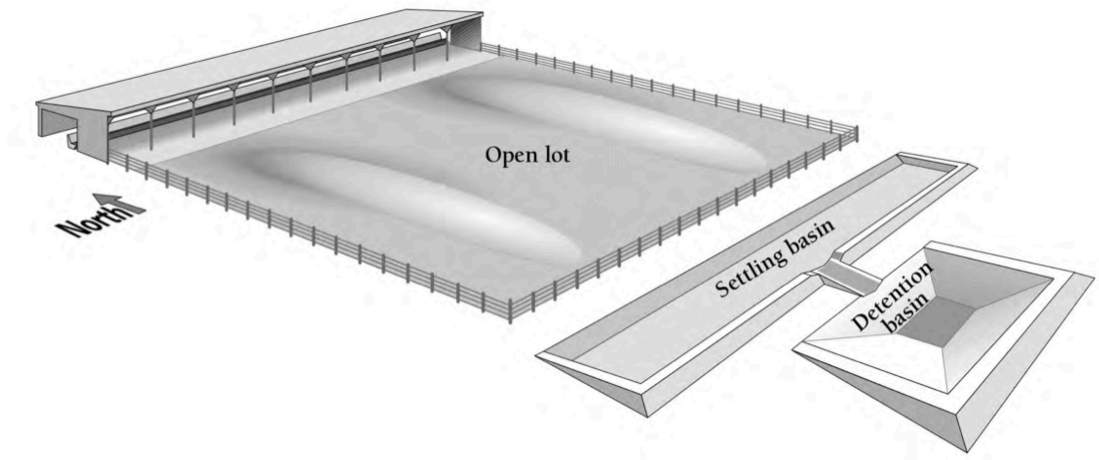

Figure 2.2 Open lot with shed (Euken et al., 2015).

2.3.3 Deep-bedded Confinement

Deep-bedded facilities typically are entirely roofed confinement structures. A minimum of 3.5 m^2 (40 sq. ft.) per head is recommended. The floor is partially or entirely covered with bedding material. Deep-bedded facilities usually are monoslope or gable roof barns, or hoop structures.

Usually, monoslopes are large, total containment steel framed and covered roof structures, oriented east-west so that the open wall to the south and a ventilation curtain along the north wall modulates, natural (flow-through) ventilation. It also minimizes the effect of northerly winds in the winter, keeps precipitation out of the building and allows sunlight to reach the back of the pens (Doran et al., 2010).

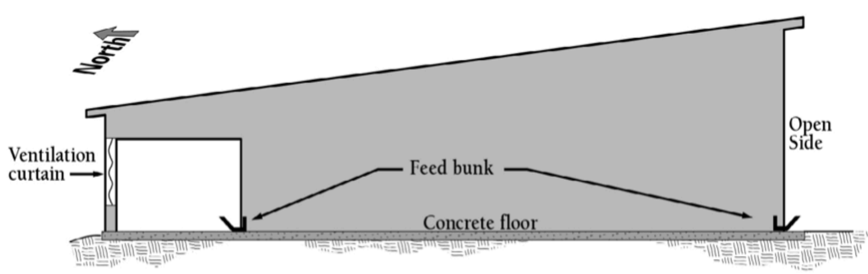

Figure 2.3 Deep-bedded confinement monoslope building (Euken et al., 2015).

Another popular deep-bedded design for finishing of cattle is the hoop building (Figure 2.4). Hoop buildings are a longer, narrower barn option and provide many of the same advantages. A bedded hoop barn incorporates low facility investment, easy management, solid manure handling and thus no feedlot runoff, low odor and dust and improved animal performance (Shouse et al., 2004). These buildings are oriented east- west, similarly to monoslope buildings.

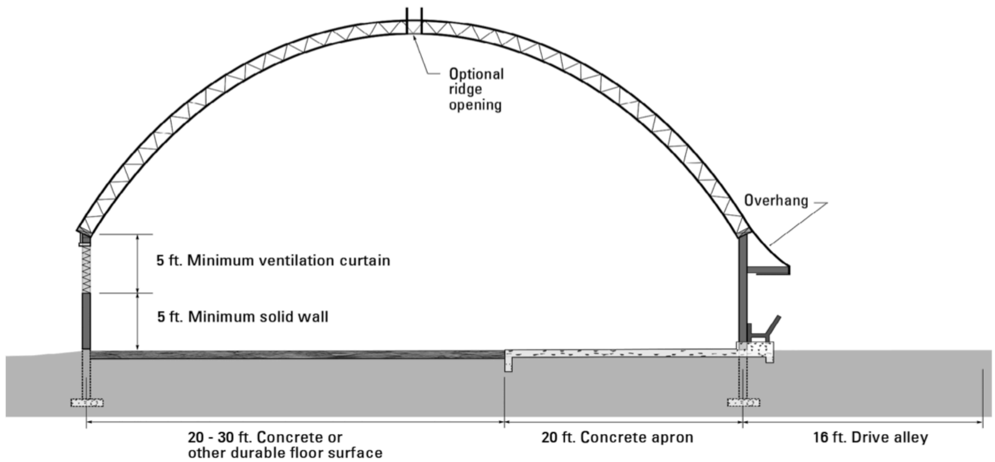

Figure 2.4 Deep-bedded confinement hoop building (Euken et al. 2015).

2.3.4 Slatted Floor Confinement

The slatted floor confinement system (Figure 2.5) has a concrete pit located below the slatted pen surface for liquid manure storage. This pit is sized to be pumped twice yearly. Cattle fed in this system are confined within the building. Approximately 2.5 m^2 (25 sq. ft.) is typically allowed per animal. On the north side of the building there is a 1.5 m (5-ft.) concrete wall. The south side of the building is commonly open-sided. The roof may be one of several designs – monoslope, gable or hoop.

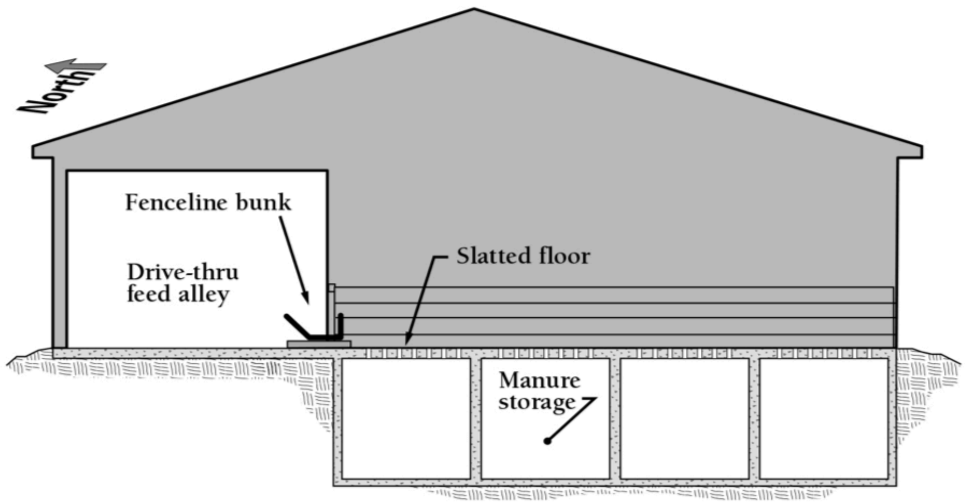

Figure 2.5 Slatted floor confinement (Euken et al. ,2015).

2.4 Types of Facilities and Manure Management

All animal feeding operations must meet basic environmental regulations to prevent runoff and protect water quality. In addition to the regulatory requirements related to manure handling, other management practices can be followed to allow improved capture and utilization of manure nutrients (Van Horn et al., 1994). When choosing a facility type, producers should consider whether they prefer to handle solid or liquid manure. Both liquid and solid manure have value but differ in manure handling equipment, cost, scheduling, and time required to clean, move, and manage manure (MWPS-18, 2000).

Each type of facility offers different options for manure storage and handling. Open feedlots typically have the lowest manure handling cost. However, manure on an open lot surface is affected by environmental factors and so it has the least amount of nutrients captured and consequently the lowest value. Manure nutrient concentration and moisture content in open lot manure are highly variable (Euken, 2010). Settled solids and manure scraped from the lot surface can either be stockpiled or applied directly to land area if available (Larney et al., 2006).

On the other hand, confinement buildings retain more manure nutrients, as they are captured in the bedding or the pit. Bedded confinement facilities typically involve more labor. The pen is bedded one or two times per week and the manure-bed pack is allowed to accumulate. Manure is stored and handled as solid, and the collection and storage of open lot runoff are eliminated. The manure-bedding mixture is scraped and removed once or twice weekly (Honeyman et al., 2008). Some deep-bedded confinement facilities may contain a short-term manure storage area such as specially designed bays between two pens, externally at either end of the barn or off-site from the facility in a stockpile area until it can be land applied (Vanderholm, 1979; Van Horn et al., 1994).

2.5 Bedded Pack Barns

2.5.1 Introduction

In the Midwestern United States, cattle-housing systems have shifted from pasture-based to indoor housing with restricted outdoor access (Barberg et al., 2007a). Outdoor exercise might be available depending on the weather conditions (Barberg et al., 2007b). There are concerns related to potential lameness, a major welfare problem in the beef industry, associated with cow housing on concrete flooring and in uncomfortable free stalls. These housing systems have a considerable influence on the overall health of the feet and legs as well as on the longevity of animals.

Livestock producers also face the challenge of finding manure management strategies and technologies that comply with environmental regulations and are economically feasible (NDESC, 2005; South Dakota NRCS, 2011). BPS might be such an alternative that will provide the farmers with the option to modernize their beef cattle facilities while minimizing capital cost (Gay, 2009).

A BPS is an alternative under-roof animal housing system for beef cattle feeding operations that livestock producers are increasingly utilizing recently instead of the traditionally used open feedlots, mostly to improve animal well-being (Bond et al., 2011). These systems require proper design, location, and sound management practices to provide a well ventilated, dry place for cattle to lie down. Producers report the benefits of these barns include improved cow comfort and cleanliness, low maintenance, reduced lameness, ease of manure handling, increased production, increased longevity, less odor and improved manure value.

Bedding materials are utilized to absorb excess moisture, to improve animal comfort and to reduce negative environmental impacts from these livestock facilities. Although bedding is a costly component of the BPS (the on-going annual costs of the bedding material must be considered), and its availability fluctuates, the system has significant implications for animal health as well as for the environment. Bedded pack systems offer a clean, dry surface for the cow to lay on thus providing excellent cow comfort levels (Barberg et al., 2007b; Gay, 2009; Janni et al., 2007). At the same time, it can be an environmentally efficient alternative to the existing manure management practices: manure is stored and handled as solid.

BPS consist of a concrete feed alley and an open bedded resting area, which is separated from the feed alley by a 0.6 m high concrete wall (Barberg et al., 2007b). The bedded pack area is 7.5- 9 m^2 (80 – 100 ft^2) per head. Compared to traditional feedlots, this allows higher animal density, so that more animals can be held in an area.

The most critical success factor for managing a BPS is providing a comfortable, dry resting surface for cattle at all times. There are variations of bedded pack barns, which include different types of building, bedding and bed pack management. The two basic types of beef bedded pack buildings are hoop structures and monoslope structures (South Dakota NRCS, 2011).

2.5.2 Bedded Monoslope Buildings and Hoop Structures

Monoslope barns have one slope to their roof and are usually naturally ventilated. They are typically positioned to take advantage of seasonal climatic conditions. This type of barns allows seasonal solar radiation and natural ventilation. This means the higher side would be facing to the south and the lower side to the north. This allows sun exposure in the winter and shade in the summer and substantial ventilation from southerly winds.

Hoop barns rely on bedding to maintain the animal environment. The floor in a hoop barn is generally made of compacted soil or concrete, allowing for the easiest cleanout. The sidewalls are made of wood or concrete with the north and south ends usually open to increase airflow. Hoop frames are constructed primarily from 5 to 7.5 cm (2- to 3-inch) round tubular steel to form a roof truss system (Shouse et al., 2004). This frame supports the tarp roof, generally made of woven polyethylene fabric, which is attached to the sidewall of the building. BPS requires enough bedding to keep the floor under the bedding pack relatively dry (Honeyman et al., 2008). Hoop barns are considered to be an improved housing option for nutrient runoff, although proper equipment and an appropriate storage area available is needed for manure management. Furthermore, concerns exist about adequate ventilation in these structures.

2.5.3 Site Selection - Orientation

Site selection is crucial. Both hoop and monoslope barns are generally orientated east-west, to take advantage of prevailing southerly summer wind direction and maximize wind-induced natural ventilation. Sufficient ventilation is needed to remove the additional animal heat and moisture that is generated. This orientation also reduces the late afternoon sunlight entering the barn. This orientation also allows the producer to minimize the effect of northerly winds in the winter and keep precipitation out of the building by adjusting the size of the curtain opening. Second, the east-west orientation allows sunlight to reach the back of the pens in the winter, enhancing cattle comfort. It is recommended that these barns be located in an open area away from other buildings, to allow for adequate ventilation (South Dakota NRCS, 2011).

The barn-building site should also be slightly elevated so that exterior surface drainage is diverted around and away from the building to minimize rain and snow runoff infiltrating into the pack.

2.5.4 Barn Layout

Bedded pack barns require proper design, proper location selection and good management to provide a comfortable, well-ventilated and dry place for cattle to lie down. BPS usually consist of a single building with adequate sidewall open area for proper ventilation. They have a large open bedded pack resting area with a 1 to 1.5 m (4 to 5 feet) wide concrete feed alley for access to the feeders and waterers. There is a 0.6 to 1.2 m (2 to 4 foot) high wall on all sides surrounding and separating the bedded pack area from the feed alley, which is helpful in managing the pack moisture (Barberg et al., 2007b). Furthermore, the wall, most commonly constructed of concrete, retains the bedding material within the barn and withstands the pressure from the bedding- manure pack.

An important part of animal well-being, performance and health is accessibility to feed and water. Cattle should be provided with access to feed and water without having to travel long distances. Feeding areas may be located in the barn or under a separate roof outside the barn. Waterers are located against the concrete wall and can generally be accessed from the feed alley only.

2.5.5 Ventilation

Proper ventilation is essential, as it promotes cattle' health. Ventilation removes heat, moisture, gases and dust created by the animals and the bedding material. Proper ventilation helps to maintain a dry bedded pack surface, retarding bacterial growth and keeping cattle cleaner. The natural air movement through the barn cools cattle in the summer, dryies the pack surface and controls dust. The orientation chosen for the barn should favor ventilation. To maintain sufficient natural ventilation under heat-stress weather conditions, the total open area of a windward barn sidewall is suggested to be at least 0.5-1 m^2 (7-11 ft^2) per cow (McFarland et al., 2013). In the case of reduced natural ventilation due to disadvantages of barn orientation, mechanical air mixing should be promoted through circulation fans.

2.5.6 Environmental Conditions in Deep-bedded Pack Structures

Choosing the environment in which beef cattle will spend the majority of their time is an important decision for livestock producers. This choice has considerable influence on productivity, health, animal well-being and farm profitability (Bewley and Taraba, 2009). In a bedded pack barn the environment, which is determined by numerous factors, including ambient temperature, air speed and relative humidity, is controlled for animals. A stressful environment can have an adverse impact on cattle performance.

The bedded pack barn contributes some improvements to animal well-being but may hinder animal performance. There is an increased infection risk, and potential for more gaseous emissions from the manure pack, including greater nitrous oxide emissions. Some other potential limitations of BPS include the following: the bedding availability that is required, the higher initial investment cost and the regular maintenance that is needed to add bedding and remove bedded pack from the barn. Improper pack management leading to wet areas will cause the pack to act like mud in lots, which will in turn reduce animal performance.

2.6 Bedding

2.6.1 Introduction

Beef cattle comfort is an essential aspect to take into consideration. Various parameters such as initial moisture content, water holding capacity and particle size distribution are important when selecting bedding material. The ideal selection would be an initially dry material, with different particle sizes that improve the water holding capacity. The bedding should also be economic and consistently available to the livestock producers.

Parameters that impact the bedding material performance are moisture content, bulk density and porosity (Wright & Inglis, 2002). Media particle size distribution is a significant factor influencing the bedding water holding capacity and bulk density. Bulk density decreases as particle size increases, since, the volume of spaces between particles increases.

In deep-bedded barns, many different types of bedding may be found, including organic (biomass) and inert (sand). When organic materials are used, ammonia volatilization is reduced, thus improving air quality in the housing facility. In the Midwest, the typical bedding types are corn and soybean stover, straw, and wood chips.

The main factors that affect bedding choice are the facility in which the cattle are housed and the current manure handling system. Additionally, the size and age of the animal and the population density, the air temperature and humidity will prescribe the type and amount of bedding needed. Bedding is usually added to the barn at regular intervals, usually ranging from every other day to once per week. More bedding is required during wet periods, for instance over the winter, to keep the bedded pack sufficiently dry (South Dakota NRCS, 2011).

2.6.2 Bedding Selection Characteristics

A number of essential factors must be considered for bedding materials selection. These include the level of absorbency, water retention/evaporation rate, carbon content and availability, density, structure, effects on animal health, labor requirements and handling systems, availability of supply and cost (Hill, 2000a). Bedding materials should contribute to the overall comfort of the animal by providing a dry, cushioned place that encourages resting. Bedding moisture content should be maintained in low levels so that it does not dramatically increase the level of microbial activity in the bedding.

Animal health and welfare are a high priority when assessing the suitability of a bedding material. Animals kept in poor environmental conditions will have impaired growth rates and often exhibit higher disease incidence. Therefore, it is essential the material be chosen with animal welfare in mind. Another important consideration when selecting an appropriate bedding material is its availability all year round and its cost. Buying bedding at the most economic time, often during harvest, is generally the least expensive option. Moreover, purchasing a year’s supply of bedding may be cost-effective, if a proper storage facility for bedding is available.

2.6.3 Water Holding Capacity

Bedding materials are porous structures where high percentage of the volume is pore space. Usually half of it consists of "macropores" and half being smaller "micro-" or "capillary" pores (Patriquin, 2004). The water drains from the larger pores by downward gravitational flow, leaving them air-filled. The micropores do not drain by gravitational flow; rather they hold water by capillary forces between the water and the bedding material surfaces. When all of the micropores are filled with water the material has reached its saturation.

The amount of water that a material can retain at the point of saturation is defined as its water holding capacity. The WHC of any material varies due to differences in initial moisture content and the degree of grinding, which alters the particle size distribution and surface area. Organic matter of smaller particle size absorbs significantly more water than coarse and medium ground particles of the same bedding material (Spiehs et al., 2013).

The WHC and rate of evaporative water loss (EWL) for some types of organic bedding materials used in livestock facilities has been also been evaluated previously, Spiehs et al. (2013) determined the WHC and rated the EWL of various bedding materials. Ten organic bedding materials were evaluated including wheat straw, switchgrass, corn stover, soybean stover, kiln-dried pine wood shavings, dried cedar, green cedar, paper, and corn cobs. Each bedding material was evaluated at a coarse-, medium- and finely-ground particle size to determine the WHC. With the exception of green cedar and corn cobs, EWL was measured at all three particle sizes available. WHC of the nine bedding materials ranged from 1.6 g H_2O (g dry bedding)$^{-1}$ for switchgrass to 3.6 g H_2O (g dry bedding)$^{-1}$ for wheat straw and corn stover. Finely ground particles absorbed significantly more water than coarse and medium ground particles of the same bedding materials (Spiehs et al., 2013). The table below (Table 2.1) shows a comparison of the WHCs of different bedding materials as found in literature (Kains et al., 2014; Doran et al., 2010; Spiehs et al., 2013; MWPS-18, 2000; Hill, 2000b; Wheeler et al., 2005; Westendorf and Krogmann, 2006). The materials compared are the same used for this research.

Table 2.1 Comparison of the WHCs as found in the literature.

Bedding Material	Hill, 2000	MWPS-18, 2000	Wheeler et al., 2005	Westendorf &Krogmann, 2006	Spiehs et al., 2013	Kains et al., 2014
Corn Cobs	2.1	2.1	2.1	2.1	2.2	2.1
Corn Stover	Medium*	2.5	2.5	2.5	3.6	2.5
Pine Shavings	1.8	2.0	3.0	2.0	3.0	2.0
Switchgrass	1.0 – 2.0**	***	***	***	1.6	***
Miscanthus	***	***	***	***	***	***
Wheat Straw	2.1	2.2	2.1	2.2	3.6	***
Soybean Stover	*	***	***	***	2.8	***

*Depends on harvesting technique **Depends on type and variety *** not reported

2.6.4 Types of Bedding Currently Used

Numerous organic bedding materials for livestock are available but their cost, availability and effectiveness varies. Wheat straw is typically the bedding material of choice for the majority of farms; however, its availability and cost is now becoming a concern. Dry, fine wood shavings or sawdust, corn or soybean stover and miscanthus are recommended as various alternative bedding materials for bedded pack.

Some of the organic bedding materials of choice for cattle are the following:

- Straw - It has good absorbency and thermal properties. It is soft, easy to handle and readily available in many areas.
- Hay (cut and dried legumes and grasses) - It is quite absorbent but one of the most expensive beddings.

- Wood Shavings – It is satisfactory as bedding, providing comfort and sufficient absorbency.
- Wood chips – Might be cheap and it needs less repeated additions. However, they provide fairly poor comfort and absorbency, and promote microbial and fungal growth. Availability may be an issue.
- Miscanthus – Although it has high moisture content, it has good absorbency. Readily available and easy to handle. It must be chopped before use.
- Sawdust – widely used as bedding material, but the cost, availability and dust are growing concerns among the producers. It has a fine particle size and provides poor air circulation. This is a highly absorbent material, encouraging the growth of bacteria.

Inert bedding materials are also used. For instance in the dairy industry sand is used. It supports less microbial growth than most organic materials but it does not absorb moisture well. It provides excellent comfort for the animals; due to its nature, an animal's body can conform directly to the material. Another example is shredded newspaper, which is cost competitive with traditional bedding materials, suitable for all livestock, highly absorbent, long lasting, clean, dust and weed free and rapidly decomposable in soil (Herbert et al., 2005).

2.6.5 Animal Health and Welfare Issues Related to Bedding

Cattle lameness is an important welfare problem in the industry and leads to considerable economic loss (Barberg et al., 2007a). Concrete flooring and uncomfortable free stalls are associated with increased incidence of lameness and hock lesions (Cook et al., 2004; Vokey et al., 2001; Weary & Taszkun, 2000).

BPS significantly influences the overall animal health and longevity. It is a good alternate housing system for animals if a reliable bedding source is available. Research has shown that cattle prefer a dry lying surface and they spend more time lying down in well-bedded stalls than in those with little or no bedding (Fregonesi et al., 2007; Tucker and Weary, 2004).

In addition to providing a well-bedded surface for the cattle, it is also important to properly maintain this bedded surface. Drissler et al. (2005) has documented that a decline in bedding levels in deep-bedded stalls that are not maintained have a dramatic effect on the stall usage (Drissler et al., 2005). The lying time declined by approximately 10 min/day for every 1 cm reduction in sand bedding (Fregonesi et al., 2007). In addition, the bedding quality also declines as the bedding becomes wet, either from exposure to the elements or from feces and urine entering the stall. Moreover, a wet bedded pack is more vulnerable to compaction.

Previous studies indicated cattle prefer bedding that contains lower moisture content during both summer and winter. Environmental conditions, mainly temperature, humidity, air velocity and the Temperature-Humidity Index (THI), has an impact on the lying time of the cattle. The THI ha been used to estimate the level of heat stress in beef cattle. Cattle lying behavior has an inverse relationship with the THI (Endres and Barberg, 2007). As THI increases cattle lay down fewer minutes per hour and increase the number of steps taken, which indicates restlessness and stress.

2.6.6 Bedding Management

Management of the bedded-pack is critical and its main objective is to maintain the bedded pack dry and clean for as long as possible. In a conventional BPS, manure is deposited directly onto the bedded pack surface; thus, maintenance of a clean, dry surface requires frequent new bedding addition. Bedding is added when the bedded pack becomes moist enough to adhere to the cattle (mostly when the wet basis moisture content is greater than about 60%). Urine, wet feces, and moisture from microbial activity are the moisture sources in a bedded-pack. Rain and snow blowing in can also wet the pack and should be avoided to the extent possible.

The amount of bedding used per addition and the frequency of its addition to the bedded pack of the barn varies. It depends on environmental factors (weather, temperature, humidity and evaporation losses), animal factors (animal density, age, amount of manure and urine produced) and finally, bedding material type. Typically, clean material is added every 1 to 5 weeks, varying by season, weather conditions, barn size, ventilation efficiency and animal density (Endres and Janni, 2008). Some livestock producers prefer to add smaller bedding amounts less frequently, such as once per week. More bedding may be used during humid or wet weather or if the barn is overcrowded. Bedding usage during the winter is greater than during the summer (South Dakota NRCS, 2011).

The bedding in the barns absorbs the water in the manure and the bedded pack acts as manure storage (Kammel, 2004). Scraped bedded pack manure is either stored in a manure bay or a designated stacking area at the end or middle of the barn. This eliminates runoff from the feeding operation and the need for runoff collection, storage, and treatment measures (South Dakota NRCS, 2011).

Although frequent changing of bedding may seem costly, in the long run it will greatly help to reduce bacterial growth (Herbert et al., 2005). For herds using the bedded pack as a winter housing system, the bedded pack material is removed at the end of the winter season. For continuously occupied barns, removal occurs every two to four months (Kammel, 2004).

In conclusion, Hill (2000) suggested that bedding is the most critical determining factor for success or failure in all types of deep bed production systems. It affects animal performance, animal behavior, animal health and the quality of the building environment.

2.7 Manure

2.7.1 Introduction

Livestock feces and urine can be either a valuable resource of nutrients or an environmental pollutant, depending on how it is managed. Manure nutrients have fertilizer value when applied on the land, are vital to plant growth and beneficial to soil and soil organisms. The nutrient content is critical as it affects land application rates and treatment techniques. Proper handling and management of manure can supplement or replace purchased commercial fertilizer while avoiding harm to the environment.

Manure properties depend on several factors: diet, protein and fiber content, animal age, stage of production, housing, and the environment (MWPS-18, 2000). The quantity, composition and consistency of manure influence the livestock facility design selection (James et al., 2006).

2.7.2 Manure Management Characteristics

Manure handling is expensive and must meet several requirements. A well-designed manure handling system should improve manure management, provide positive environmental protection and allow maximum utilization of manure nutrients. The manure management system includes collection, transfer, storage, possible treatment and land application. When selecting a manure management system, a producer should consider animal age, size and density, housing, bedding and labor requirements (James et al., 2006). Additionally, manure characteristics influence the equipment needed for collecting, handling, treating, transporting and storing. Many physical, chemical, and biological processes can alter manure characteristics from its original as-excreted form (ASABE D384.2, 2005).

Manure can be classified based on how it is handled as consistency changes from liquid to solid (MWPS-18 2000). There are several different manure management strategies – liquid (lagoon) systems, slurry systems and solid systems are the common choices (Van Horn et al., 1997).

- *Liquid manure* is usually 1 to 2% solids (4% maximum) and is common with flushing and lagoon systems. Liquid manure has the most water added or solids removed from a low-solids content fluid that can be handled with irrigation equipment.
- *Slurry manure* is a combination of feces and urine with little organic bedding. Manure with 4–10% solids content can usually be handled as a liquid but may need special pumps. Producers may have to add water to handle the manure as a liquid.

- *Semi-solid* manure is in the 10–20% solids content range. Handling characteristics vary depending on the types of solids present. Usually, it has little bedding and no extra liquid added. Little drying of semi-solid manure occurs before handling.
- S*olid* manure with 20–25% solids content can usually be handled with front-end loaders or pitchforks. Solid manure often has a relatively large amount of bedding added and it can be stacked. It is a combination of bedding, feces and urine such as that found in a bedded pack barn or open lots with good drainage.

Semi-solid and solid manure can be handled with tractor scrapers, front-end loaders, or mechanical scrapers. Conventional box or flail spreaders are common for land application.

2.8 Crucial Design Criteria

2.8.1 Manure and Bedding Volume Storage Requirement in Bedded Pack Barns

Beef cattle manure is characterized and treated as a solid in BPS. Solid manure can be stored in an open or covered stacking slab with or without retaining walls. The bed pack is allowed to pile up for six months to a year. Illinois state regulations require that solid manure storage systems are sized to allow manure-bedding mixture to be stored for at least six months. Research has been conducted in the past to find means of precisely estimating the total manure-bedding mixture storage needs for BPS.

There are several techniques for estimating the final storage volume required over time for the manure-bedding mixture. Three primary methods have been compared (Pepple and Gates, 2013). The first two methods were originated from MWPS-18 (2000) and used the same fundamental total storage volume equation, but they differed in the way total added bedding volumes were determined. To determine the total bedding volume needed, assumptions related to the final bed pack moisture and the absorption of free water were incorporated in the calculations. According to MWPS – 18, to estimate the total mass of bedding-manure mixture, the manure volume produced per animal per day (from ASABE D384.2, 2005 - solids and liquids) should be added to half of the volume of bedding added. Bedding volume is assumed to be reduced by one-half during use. The third method was a mass balance approach developed by South Dakota Natural Resources Conservation Service (South Dakota NRCS, 2011; Pepple and Gates, 2013). Reported literature values for daily bedding amounts were used for this method. The South Dakota NRCS method assumes evaporation losses occur within the barn and the bed pack remains dryer without using extra bedding. These methods are discussed more extensively in the Materials and Methods chapter.

For these three methods mentioned above the primary differences were the assumptions related to moisture in the bed pack. The first method require a final dry matter content of 25%, which is supposed to prevent potential seepage to occur and maintain manure’s stackability (Pepple and Gates, 2013). It also assumed no losses of moisture occurring through evaporation or other means within the system. The second method considered a fixed percentage of free water in the bed pack to be absorbed by the addition of bedding and also disregarded evaporation within the system, similarly to the first method. In particular, 50% of bedding volume added was lost, supposedly from compaction. Naturally occurring evaporation losses within the barn were assumed for the last method, which did not require the addition of bedding. Finally, the water holding capacity values used in this method were found in the literature (Spiehs et al., 2013).

A comparison of these three total storage volume estimation methods showed significantly different bedding volume recommendations. The daily amount of bedding required daily per animal ranged from 1.9 to 6.6 kg (4.1 to 14.5 lb). Total storage volume estimates ranged from 0.016 to 0.064 m^3 (0.55 to 2.25 ft^3) per animal per day. According to Pepple and Gates (2013) these significant required storage amount variations are important for livestock producers wishing to construct a BPS in Illinois compared to surrounding states in terms of both capital and operational cost (Pepple and Gates, 2013).

2.9 Conclusions

Although extended research has been conducted, insufficient data exists to accurately estimate the total manure volume storage required for these deep bed pack systems. This is directly related to the lack of evidence of what is the impact on water holding capacities when mixing bedding materials with manure and the final manure-bedding mixture total solids (TS) at saturation.

In order to accurately design these systems, temporal characterization of the environmental conditions within the bed pack needs to be done. This includes determining the effects on bedding WHC by the addition of manure and naturally occurring evaporation losses within the system on bed pack dry matter content.

The comparison of the three total storage volume estimation methods used in BPS showed highly different volume recommendations. These results illustrated that a bedded pack barn constructed in Illinois needs to be three times the size of one built in a neighbor state for the same number of animals. Subsequently, both capital and operation expenditures for a barn of such a size would be increased. In practice, these results are very important for livestock producers who are willing to construct and utilize a solid manure bed pack system in Illinois which is, financially, more efficient compared to previous years and surrounding states.

CHAPTER 3. MATERIALS AND METHODS

3.1 Bedding Material Selection and Processing

Bedding material selection was made according to what producers have been using for centuries as livestock bedding, what materials are currently reported in literature, and which are available in Illinois. Producers have traditionally used locally available crop biomass and wood-based bedding materials for livestock bedding. Corn stover, wheat and soybean straw, wood shavings and ground corn cobs have all been recommended in extension publications as possible bedding materials for beef facilities (Kains et al., 2014; Doran, Euken, and Spiehs, 2010; Spiehs et al., 2013; MWPS-18, 2000; Hill, 2000b; Wheeler et al.,, 2005; Westendorf and Krogmann, 2006). Doran et al., 2010 reported that the most common bedding material used in deep-bedded cattle facilities is corn stover, although wheat straw, soybean stover and corn cobs have also been used. Of the seven organic bedding materials evaluated in this research, corn stover, corn cobs, wheat straw, and soybean stover are traditionally used in livestock facilities and can be easily found in Illinois. Additional materials evaluated were pine shavings (included in literature) and biomass from miscanthus and switchgrass (available in the broader Illinois area). Corn cob, corn stover, soybean stover, miscanthus and switchgrass were obtained from the University of Illinois research farm. Wheat straw was provided by Professor Morgan Hayes. Finally, pine shavings were purchased on-line.

Corn cobs and pine shavings were received and evaluated as a granulated product. Coarse corn stover and soybean stover were ground through a 1” hammermil, as pre-treatment, at the Energy Biosciences Institute's Energy Farm. Switchgrass was already ground; thus, no further processing was needed. Laboratory scissors were used for miscanthus and wheat straw particle size reduction, as needed.

3.2 Initial Bedding Material Characterization

3.2.1 Total Solids and Moisture Content

The total solids content of bedding (TS_b) was determined according to Standard Method 2540B for total solids (APHA, AWWA, and WEF, 2012). The procedure specifies that small aluminum containers are loaded with a small amount of chopped or ground bedding material (5-10 g) and placed in an oven at 105°C for 24 h, until completely dry. The initial and final (after drying) weights were measured. All samples were done in triplicate. The detailed experimental procedure used is in Appendix A.

The TS_b content of the bedding material is calculated as follows:

$$TS_b = \frac{M_{dm}}{M_T} \quad (1)$$

where:

TS_b = Total Solids, g dry matter (g wet sample)$^{-1}$

M_{dm} = Mass of Dry Matter, g

M_T = Total Mass of Wet Quantity, g

The initial moisture content wet basis (MC_{wb}), the quantity of water contained in the bedding material, was determined by the following equation:

$$MC_{wb} = 1 - TS_b \quad (2)$$

where:

MC_{wb} = Moisture Content as is, g H_2O (g wet mixture)$^{-1}$

3.2.2 Particle Size Distribution

Bedding materials were characterized for their particle size distribution. The particle size was determined following the ASAE Standard Method of Determining and Expressing Fineness of Feed Materials by Sieving (ANSI/ASAE S319.4, 2008). However, only 12.5mm and 6.3mm sieves (½” and ¼” respectively) (ASTM E11, Hogentogler & Co. Inc., Columbia, MD, USA) were used, providing three particle size ranges. The sieve series selected was based on the range of particles in the sample. A bedding sample of 100 g (corn cobs) or 20 g (for the rest of the materials) was placed in the stack of sieves arranged from the largest to the smallest opening. Manual shaking was performed and then sieving was done for 10 min. The mass on each sieve was determined at 1-min intervals and if the mass on the smallest sieve changed by less than 0.1% the sieving is considered complete. The test sieves were held in one hand and were inclined at an angle of about 20° from horizontal and tapped approximately 120 times a minute with the other hand. After tapping, the test sieve was returned to a horizontal position turned 90° and tapped hard by hand against the sieve frame. After sieving, the mass retained on each sieve was weighed.

3.2.3 Bulk Density

Bulk densities of ground bedding material were determined following the ASAE standard method S269.4 DEC01 (ASABE Standards, 2007) for cubes, pellets, and crumbles. The container used was a 1000 mL cylindrical glass container. The container was filled with the bedding material, which was poured from a height to enable the free flowing of the sample particles. The weight of the filled container was recorded and the net weight was obtained by subtracting the weight of the empty container. Bulk density was calculated by dividing the mass of the bedding sample that occupied the container over the container volume. Each measurement was repeated three times using a different bedding sample.

3.2.4 Baseline Water Holding Capacity

The baseline WHC for bedding materials was determined using the Standard Method for Determining WHC of Fiber Mulches for Hydraulic Planting (ASTM D7367 - 07, 2007) using 15 g of bedding material as the method describes and a bigger sample size of 45 g. Three replications were done for each bedding sample size. The value for the WHC obtained with this method, was compared to values reported in the literature to evaluate the method.

WHC is equivalent to dry basis moisture content. Thus, it is calculated with the following formula:

$$\mathrm{WHC} = \frac{M_w}{M_{dm}} \quad (3)$$

Where,

WHC = Water Holding Capacity, g H_2O (g dry matter in sample)$^{-1}$

M_w = Mass of Water in Sample at Saturation, g H_2O

M_{dm} = Mass of Dry Matter, g

3.3 Manure Characterization and Processing

The manure used for these experiments was collected from the University of Illinois Beef Research Farm. Manure was collected fresh (as excreted) from the slatted floor surface. The collected manure was at 18 – 23% initial TS and it was diluted with distilled water to obtain approximately 4%, 8%, 12% and 16% TS_m. Sometimes the initial manure had lower than 16% TS_m content; thus, a part of it was dried in the oven to achieve the desired 16% TS_m. The TS content of manure slurry used for the experiments for the determination of WHC, was evaluated using the Standard Method SM 2540B (SM 2540B 1998; APHA, AWWA, and WEF, 2012)– see Appendix A.

3.4 Manure – Bedding Mixture Water Holding Capacity

3.4.1 Basic Approach

The ASTM D7367 – 07 Standard Method for the determination of WHC served as a basis for determining the WHC of manure – bedding mixtures, but minor modifications were introduced. In particular, instead of water, only manure slurry was added to the bedding at the beginning of the experiment. Furthermore, the manure – bedding mixture was left to rest horizontally for 5 min before draining and lastly the sample was dried in the oven.

The experimental procedure for WHC was as follows: 15g bedding samples, with known TS_b and MC, were placed in a mixing bowl and well-mixed manure slurry, at room temperature, was added. The mixture was blended for 5 min with a kitchen mixer at a low setting. No water was added in the bowl. The mixture (manure and bedding) was then completely removed with a spatula from the mixing bowl, placed and distributed evenly across an ASTM E11 no. 8 test sieve (ASTM E11 no. 8 test sieve, Dual Manufacturing Co, Franklin Park, IL, USA), of known weight, with its pan underneath. The sieve and the mixture were completely submerged in manure slurry for 30 min. After removal from the manure slurry, the assembly sat horizontally for 5 min and then drained by positioning at a 20-30° angle for another 3 min. A lid on top and the pan under the sieve were used to prevent from evaporation losses during draining. The sieve pan exterior surfaces were wiped with a paper towel and the sieve with the mixture and the pan were weighed as a system. All three parts of the system (sieve, pan, and mixture) were placed in an oven and dried at 103 – 105 °C for 24 h. When the samples were taken out of the oven, they were placed in glass desiccators for 2-3 h to cool to room temperature. The weight of the dried mixture and container was recorded.

3.4.2 Preliminary experiments

Preliminary experiments were devised to evaluate if the experimental method was the appropriate for use with manure mixtures and whether there were any issues affecting the results or modifications that should be introduced. Corn cob bedding was used during the preliminary testing. WHC of corn cob bedding with manure added at two different solids contents (8% and 12%) was determined following the procedure described above.

Sample Size Effect

The experiment as described in the “Basic Approach” was replicated three times using two sieves and two draining times (3 and 15 min). A factorial analysis (two-way ANOVA with replication) was performed using the statistical software R (R Core Team 2012) to test for drain time or sieve effect.

The above experimental procedure was repeated using a bigger sample size, of 45g of corn cobs. A first set of experiments was done using 45g of bedding material, 30 min of submerging the sieve with the mixture in the manure slurry (8% TS_m), then the sample was allowed to rest horizontally for 5 min and to drain prior to weighing for10 min.

Soaking Time

Experiments were conducted to determine the optimum soaking time when manure is used in place of water to evaluate the WHC. Soaking times of 45, 60, 75, 90 min, 6, 18 and 24 h were evaluated for two manure total solids contents (8% and 12%). All samples were allowed to drain for 10 min.

The selected soaking time for the determination of WHC with manure addition of corn cobs for 8% and 12% TS_m was 6 h. A t-test for equal means (comparing the mean WHC value after 6 h of submerging in the manure slurry and the mean WHC value after 24 h of submerging) was conducted.

The developed SOP to measure the WHC with manure addition of corn cobs for both percentages of TS included 6 h of soaking the mixture sample in the manure slurry, 5 min resting horizontally and 10 min draining in an angle. Eight replicates were done for the 8% TS_m and eight for the 12% TS_m. Not all of the eight replications were done simultaneously. This was an experimental technique used to reduce the impact of randomness on the measurements and to avoid bias errors. The measurements had to be statistically independent, so that the average would actually be a better statistic but with wider standard deviation range. The above experimental procedure was followed to determine corn cob WHC with 16% TS_m manure addition.

3.4.3 Adjustments to WHC Method

All seven bedding materials were tested for WHC with manure with 4%, 8%, 12%, 16% TS manure addition. The SOP developed during the preliminary testing was followed, but with some additional adjustments. The final approach of the experimental procedure included that the mixture was completely submerged in manure slurry 24 h (due to logistical issues) and the use of subsamples was introduced. This was to ensure the bedding sample was completely dry after 24 h in the oven. From each sieve three subsamples of the saturated manure-bedding mixture were taken. These were placed in pre-weighed small aluminum containers, weighed and then they were placed in the oven and dried at 103 – 105°C for 24 h. Upon removal from the oven, the subsamples were placed in glass desiccators for 2-3 h to cool to room temperature. The weight of each dried mixture in the aluminum container was recorded. This final experimental protocol described in detail in Appendix B.

At least six replications (mostly nine) were done for each bedding material WHC and each manure TS_m content. Not all of the replications were done on the same day, to avoid bias errors.

WHCs with manure addition was calculated using the following formula:

$$WHC_{mix} = = \frac{M_{mix,wb}}{M_{mix,db}} \quad (4)$$

where:

WHC_{mix}= Manure-Bedding Mixture Water Holding Capacity, g H_2O (g dry mixture)$^{-1}$

$M_{mix,wb}$ = Mass of the Manure-Bedding Mixture at Saturation (wet basis), g H_2O

$M_{mix,db}$ = Mass of Dry Manure-Bedding Mixture, g

All WHC values reported for these experiments, are normalized to a nominal manure TS_m content calculated as follows:

$$WHC_n = \frac{WHCmix \;\; TSm}{\alpha} \quad (5)$$

where:

α = Nominal Value of Total Solids, (0.04, 0.08, 0.12 or 0.16)

The units for the WHC_n are: g H_2O (g dry mixture)$^{-1}$ and include manure solids content accumulated in the denominator of equation (5).

Finally, WHC can also be expressed per unit of dry bedding (WHC_b):

$$WHC_b = = \frac{M_{mix,wb}}{M_{b,db}} \tag{6}$$

where:

WHC_b= Manure-Bedding Mixture WHC Expressed by dry matter, g H_2O (g dry bedding)$^{-1}$

$M_{mix,wb}$ = Mass of the Manure-Bedding Mixture at Saturation (wet basis), g H_2O

$M_{b,db}$ = Mass of Dry Bedding, g

The different WHCs reported in this work are summarized:

- baseline WHC using just water, g H_2O (g dry bedding)$^{-1}$
- WHC_{mix} g H_2O (g dry mixture)$^{-1}$
- WHC_n normalized for a nominal manure TS_m content, g H_2O (g dry mixture)$^{-1}$
- WHC_b expressed by bedding, g H_2O (g dry bedding)$^{-1}$

3.5 Crucial Design Criteria

Illinois regulations require that solid manure storage systems provide for at least six months of storage. Research has been conducted in the past to find means of precisely estimating the total storage needs for BPS. Three methods for estimating the final storage volume required over time for the manure-bedding mixture have been compared (Pepple and Gates, 2013), and resulted in significantly different volume recommendations. According to Pepple and Gates (2013) the amount of bedding required daily per animal ranged from 1.9 to 6.6 kg (4.1 to 14.5 lb). Total storage volume estimates ranged from 0.016 to 0.064 m^3 (0.55 to 2.25 ft^3) per animal per day. These significant storage requirement variations are important for livestock producers wishing to construct a BPS in Illinois compared to surrounding states in terms of both capital and operation cost (Pepple and Gates, 2013).

Using the same methods mentioned and the data from this research work the total storage volume was determined. These are outlined below.

3.5.1 Amount of Bedding Needed - Total Storage Volume Required

MWPS-18 Method 1

To determine the total storage volume needed, assumptions related to the final bed pack moisture content and the absorption of free water are incorporated into the calculations. According to MWPS–18, bedding volume is assumed to be reduced by one-half during use. Thus, to estimate the total mass of bedding-manure mixture, the manure volume produced per animal per day (from ASABE D384.2, 2005 - solids and liquids) is added to half of the volume of bedding per day, per equation (7):

$$V_T = V_m + \frac{1}{2} V_b \tag{7}$$

where:

V_T= Total storage volume needed, $m^3\ hd^{-1}d^{-1}$

V_m= Total manure volume, $m^3\ hd^{-1}d^{-1}$

V_b= Total bedding volume, $m^3\ hd^{-1}d^{-1}$

The method limits that the bed pack has final total solids content to 25%, to reduce potential seepage and to maintain the ability to stack the manure mixture (Pepple & Gates, 2013). It also ignores moisture losses from evaporation or other means within the system. Daily manure production mass and volume values are used from the ASABE D384.2 standard (29.1 kg $hd^{-1}d^{-1}$ and 0.029 $m^3\ hd^{-1}d^{-1}$, respectively). The total amount of bedding required was determined using the following figure (Figure 3.1). This figure was based on MWPS-18 and updated by Pepple and Gates (2013) for current manure production standards.

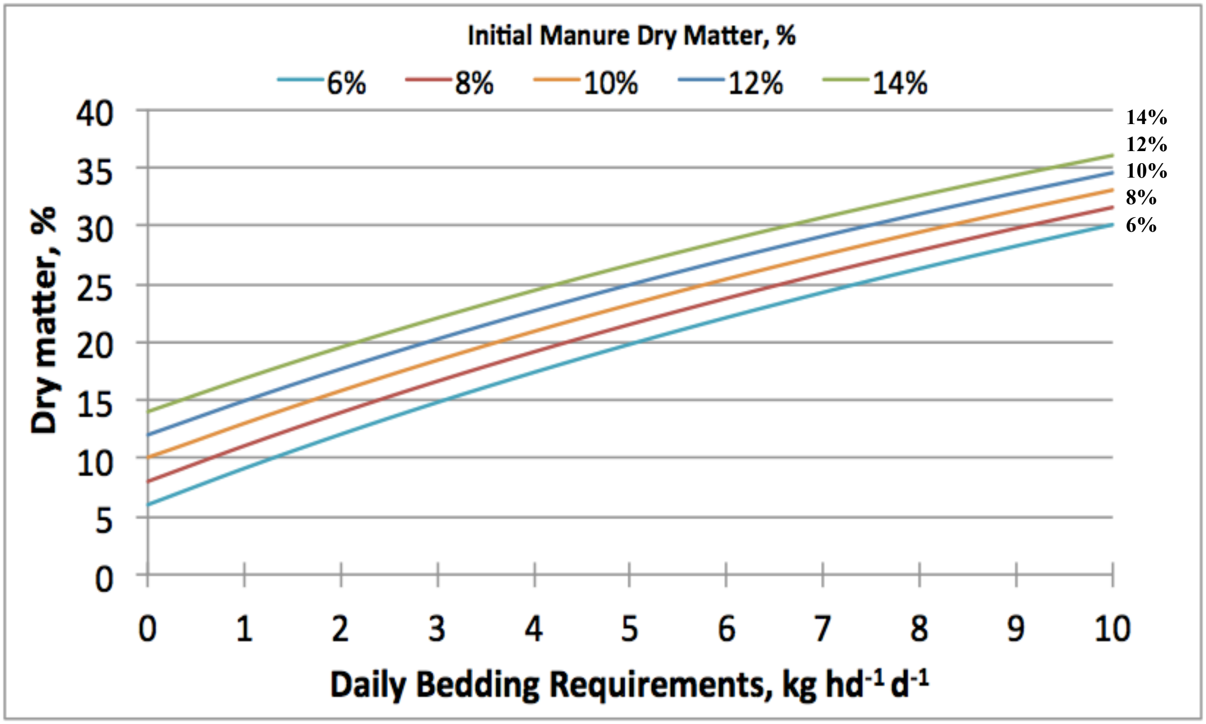

Figure 3.1 Daily bedding requirements –Note that dry matter (%) is equivalent to TS (%). (Pepple and Gates 2013).

MWPS-18 Method 2

The second method uses the same equation (equation 7), however the amount of bedding needed was calculated based on the WHC_b for each bedding material (equation 8). This equation was generated by Pepple and Gates (2013). Similarly to the first method, it neglects evaporation losses within the system. It assumes that 25% of the liquid fraction of manure is absorbed by the bedding.

$$M_b = \frac{Mm * MCm}{WHCb} \; MC_{ab} \tag{8}$$

where:

M_b= Total mass of bedding required, kg $hd^{-1}d^{-1}$

M_m= Total mass of manure produced, kg $hd^{-1}d^{-1}$

MC_m= Moisture content of manure, % (dry basis)

MC_{ab}= Desired moisture absorbed by bedding, % (assumed 25%)

WHC_b= Water holding capacity, g H_2O (g dry bedding)$^{-1}$

To determine the total bedding volume, the mass of the bedding from equation (8) is divided by the bulk density of each bedding material.

$$V_b = \frac{M_b}{\rho_b} \tag{9}$$

where:

ρ_b= Bedding bulk density, kg m^{-3}

South Dakota NRCS Method 3

The third method is a mass balance approach developed by South Dakota Natural Resources Conservation Service (South Dakota NRCS, 2011). Reported literature values for daily bedding amounts were used for this method: 2.4 kg $hd^{-1}d^{-1}$ for hoop structures and 2.8 kg $hd^{-1}d^{-1}$ for monoslope buildings. The final bed pack mass is determined by the following equation:

$$M_{bp} = \frac{M_{m,db} + M_{b,db}}{1 - MC_{bp}} \tag{10}$$

where:

M_{bp}= Total mass of bed pack, kg $hd^{-1}d^{-1}$

$M_{m,db}$= Mass of manure, dry, kg $hd^{-1}d^{-1}$

$M_{b,db}$= Mass of bedding, dry, kg $hd^{-1}d^{-1}$

MC_{bp}= Moisture content of bed pack, decimal (dry basis)

The final pack volume is calculated by dividing the total bed pack mass by the final bed pack density.

$$V_{bp} = \frac{M_{bp}}{\rho_{bp}} \tag{11}$$

where:

ρ_{bp}= Bed pack bulk density, kg m^{-3} (assumed 932.2 kg m^{-3})

3.5.2 Statistical Analysis

During the preliminary testing, the procedure described in the "Basic Approach" was performed three times using two sieves and two draining times (3 and 15 min) each. These were considered replications in time. A factorial analysis (two-way ANOVA with replication) was performed using the statistical software R (R Core Team 2012) to test for effects of drain time or sieve.

When the sample size was enlarged more soaking time was assumed to be necessary to ensure saturation. Experiments were conducted to determine the minimum soaking time in manure slurry to evaluate the WHC. For each soaking time a t-test for equal means in WHCs between the two sample sizes was conducted to test for sample size effect (n=3).

The selected soaking time for the determination of WHC with manure was 6 h. A t-test for equal means (comparing the mean WHC value after 6 h of submerging in the manure slurry and the mean WHC value after 24 h of submerging) was conducted (n=2 replications per soaking time).

T-tests for equal means within each bedding material were done for WHC_n,WHC_b, and TS_{mix} to indicate significant differences among the TS_m of the same material. Six to nine replications were made for each material, and they were not all done simultaneously to avoid bias errors from non-random effects.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Initial Bedding Material Characterization

Table 4.1 summarizes the initial bedding material characterization. Bedding materials initial total solids, their particle size distribution (PSD) percentages, wet bulk density and baseline water holding capacity are included.

4.1.1 Total Solids and Moisture Content

All bedding materials used for the experiments had approximately 92% initial TS_b (total solids of bedding) (Table 4.1) as determined according to the Standard Method 2540B for total solids (APHA, AWWA, and WEF, 2012). TS_b ranged from 91.1% (corn and soybean stover) to 93.9% (pine savings) with standard deviations of 2.3% or less.

Table 4.1 Initial bedding material characterization. Summary table for bedding material TS_b, particle size distribution (PSD), bulk density and baseline WHC (n=3 replications).

	TS_b (%)	PSD (%)			Bulk Density (kg m^{-3})	Baseline WHC (45g) (g H_2O (g dry bedding)$^{-1}$)
		Coarse[a]	Medium[b]	Fine[c]		
Corn Cobs	91.7 (2.15)	2.9 (1.11)	49.1 (6.72)	48.0 (7.34)	216.5 (8.2)	1.9 (0.01)
Corn Stover	91.1 (2.30)	13.3 (4.62)	35.3 (5.20)	51.3 (9.75)	39.3 (4.4)	3.9 (0.09)
Pine Shavings	93.9 (1.42)	3.0 (2.29)	27.6 (4.8)	69.3 (6.71)	64.6 (4.5)	2.2 (0.03)
Switchgrass	92.5 (1.81)	2.5 (1.32)	8.5 (1.00)	89.0 (2.29)	77.5 (3.8)	1.9 (0.03)
Miscanthus	92.6 (1.61)	32.1 (5.50)	42.5 (6.50)	25.3 (2.75)	32 (9.3)	1.2 (0.04)
Wheat Straw	92.7 (2.00)	27.3 (7.09)	29.3 (2.02)	43.3 (6.29)	24.3 (6.8)	2.8 (0.06)
Soybean Stover	91.1 (2.34)	3.7 (2.02)	15.8 (4.50)	80.3 (6.66)	64.8 (5.0)	2.6 (0.04)

Mean (SD), [a]> 12.5 mm, [b] 12.5 to 6.3 mm, [c]< 6.3 mm

4.1.2 Particle Size Distribution

Sieve analysis to define the particle size distribution of each bedding material was performed in triplicate and the mean (SD) percentage of each particle size range (coarse, medium, fine) is reported (Table 4.1). Particles that remained on the 12.5 mm screen were defined as coarse particles, those that passed through the 12.5 mm screen but not from the 6.3 mm screen were defined as medium particles and the remainder passing through to the collecting pan, were defined as fine particles.

The majority of the bedding materials tested consisted of at least 50% of fine particles (Figure 4.1). Soybean stover, switchgrass and pine shavings were comprised of even more fine particles (70% - 90%). The particle size distribution alters WHC since organic matter of smaller particle size absorbs significantly more water than coarse and medium ground particles of the same bedding material (Spiehs et al., 2013).

Corn cobs, pine shavings, switchgrass and soybean stover had significantly lower percentage of coarse particles (below 4%), while miscanthus and wheat straw had almost 30% coarse particles. These latter two bedding materials were uniformly distributed among the three size ranges.

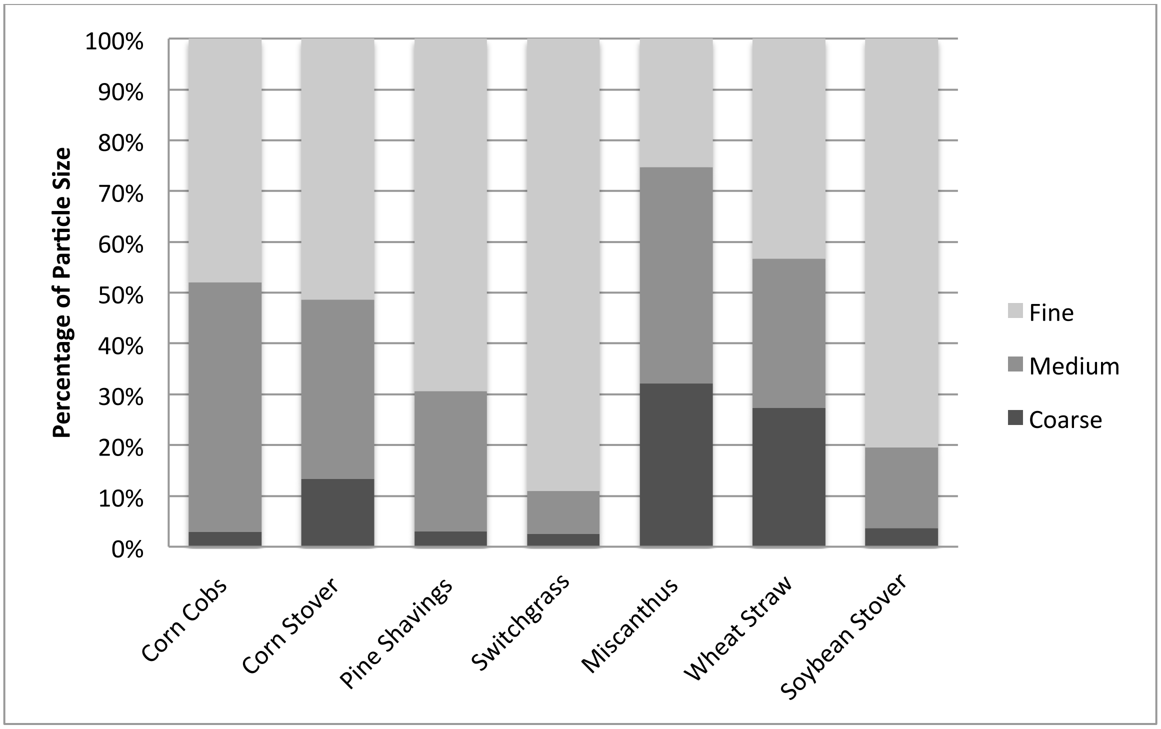

Figure 4.1 Particle size distribution of the seven bedding materials.

4.1.3 Bulk Density

The bulk density of the bedding materials ranged from 216.5 ± 8.2 kg m^{-3} for corn cobs to 24.3 ± 6.8 kg m^{-3} for wheat straw. Corn stover, pine shavings, switchgrass, miscanthus and soybean stover bulk density were 39.3 ± 4.4 kg m^{-3}, 64.6± 4.5 kg m^{-3}, 77.5 ± 3.8 kg m^{-3}, 32 ± 9.3 kg m^{-3} and 64.8 ± 5.0 kg m^{-3}, respectively. The bulk density increases as the particle size decreases. All bedding materials bulk density values are included in Table 4.1.

4.1.4 Baseline Water Holding Capacity

Baseline WHC was determined following the Standard Method ASTM D7367 - 07, using 15 g of bedding material per the method and a larger sample size of 45 g. Table 4.2 shows the baseline WHC values for both bedding sample sizes. There was a difference in baseline WHC with different sample sizes for corn stover, switchgrass, miscanthus and wheat straw ($P < 0.05$). In all materials, the larger sample size gave a numerically lower value of baseline WHC. This means the sample size affects the baseline WHC values.

Table 4.2 Baseline WHC for all bedding materials using 15 g and 45 g of bedding (n=3 replications).

Bedding Material	Baseline WHC (g H_2O (g dry bedding)$^{-1}$)	
	Sample size 15 g	Sample size 45 g
Corn Cobs [a]	2.1 (0.17)	1.9 (0.01)
Corn Stover [b]	5.0 (0.31)	3.9 (0.09)
Pine Shavings [a]	2.2 (0.08)	2.2 (0.03)
Switchgrass [b]	2.4 (0.07)	1.9 (0.03)
Miscanthus [b]	1.4 (0.05)	1.2 (0.04)
Wheat Straw [b]	3.2 (0.10)	2.8 (0.06)
Soybean Stover [a]	2.7 (0.13)	2.6 (0.04)

[a] there is no significant difference between the baseline WHC values of the two different sample sizes, ($P > 0.05$); [b] there is significant difference between the baseline WHC values of the two different sample sizes, ($P < 0.05$); Mean (SD)

Miscanthus had the lowest baseline WHC of all bedding materials. For the 15 g samples, the baseline WHC was 1.4 ± 0.05 g of water per g of dry bedding and for the 45 g samples WHC was 1.2 ± 0.04 g of water per g of dry bedding of bedding. There are no published values in the literature for miscanthus WHC to make comparisons. Corn cobs, pine shavings and switchgrass had slightly higher baseline WHC than miscanthus (from 1.9 g of water per g of dry bedding for 45 g of corn cob and switchgrass bedding to 2.4 g of water per g of dry bedding for 15 g of switchgrass). All of these WHC values were comparable to what is reported in literature. Wheat straw and soybean stover baseline WHCs for 15 g samples was 3.2 ± 0.10 and 2.7 ± 0.13 g of water per g of dry bedding and for 45 g samples was 2.8 ± 0.06 and 2.6 ± 0.04 g of water per g of dry bedding of bedding, respectively. Spiehs et al. (2013) reported a mean WHC of 3.6 g of water per g of dry bedding for wheat straw while other studies (MWPS-18, 2000, Wheeler et al., 2005, Westendorf &Krogmann, 2006) have shown much lower values (2.1- 2.2 g of water per g of dry bedding). Finally, corn stover baseline WHC with 15 g samples was 5.0 ± 0.31 g of water per g of dry bedding and for 45 g samples WHC was 3.9 ± 0.09 g of water per g of dry bedding. Spiehs et al. (2013) reported mean WHC of 3.6 g/g (4.6 g/g for fine particles) and MWPS-18 stated a value of 2.5 g/g.

For the purposes of this research and to be able to make direct comparisons between the baseline WHC and the WHC of bedding materials when manure is added, the baseline WHC refers to the values found for 45 g sample size. Table 4.3 shows a comparison between the baseline WHC as evaluated during this research and the WHC values as reported in literature. All bedding materials baseline WHC fall within the range of the WHC reported in literature, except miscanthus (not reported) and corn stover baseline WHC is slightly greater. This difference may be related to the specific variety of the crop harvested and tested, the initial moisture content, or the particle size distribution. Fine particles absorb significantly more water than larger particles of the same bedding materials (Spiehs et al., 2013), so if there are more fines in the corn cob used in this study it could explain the differences between the WHC values reported. The corn stover used for the determination of manure- bedding mixture WHC consisted mostly of fine particles.

Spiehs et al. (2013) evaluated each bedding material at three different particle sizes (coarse, medium, and finely ground) and reported WHC for these different size ranges. In this study, bedding materials were tested without first separating the samples according to the particle size distribution. Instead, the particle size distribution was tested and a single WHC is reported. Using the percentage of coarse, medium, and fine particles in each bedding material from this study and the WHC reported by Spiehs a direct comparison of the values can be made. For instance, corn stover's WHC was 3.9 g of water per g of dry bedding while Spiehs et al. (2013) reported mean WHC of 3.6 g/g. Spiehs WHC values for each particle size of corn stover were multiplied by the PSD percentage measured during this research. The result shows that the WHC of corn stover is equal to the measured value.

Table 4.3 Comparison of the baseline WHC in this study with WHC for the same bedding materials reported in the literature.

Bedding Material	Baseline WHC (This study)	Hill, 2000	MWPS-18, 2000	Wheeler et al., 2005	Westendorf &Krogmann, 2006	Spiehs et al., 2013	Kains et al., 2014
Corn Cobs	***1.9***	2.1	2.1	2.1	2.1	2.2	2.1
Corn Stover	***3.9***	Medium*	2.5	2.5	2.5	3.6	2.5
Pine Shavings	***2.2***	1.8	2.0	3.0	2.0	3.0	2.0
Switchgrass	***1.9***	1.0 – 2.0**	***	***	***	1.6	***
Miscanthus	***1.2***	***	***	***	***	***	***
Wheat Straw	***2.8***	2.1	2.2	2.1	2.2	3.6	***
Soybean Stover	***2.6***	*	***	***	***	2.8	***

*Depends on harvesting technic **Depends on type and variety *** not reported

4.2 Manure – Bedding Mixture Water Holding Capacity

4.2.1 Preliminary experiments

Apparent Sample Size Effect

The WHC of corn cob bedding with manure addition was determined during the preliminary testing. The collected manure was at 18 – 23% initial TS_m and it was dissolved with distilled water to achieve lower total solids concentrations. When 8% TS_m manure was added to 15 g of corn cob media, corn cobs WHC was determined to have an average normalized value (WHC_n) of 5.8 ± 0.1 g of water per g of dry mixture. WHC increased significantly with manure addition. This is presumably because of the existence of fine solid particles in the manure slurry, which adhere to the coarse surface of corn cobs. These fine solid particles have the ability to hold more water, by increasing the sample surface and reducing the particle size distribution in the sample.

For each drain time (3 and 15 min) and for each sieve, the experiment was replicated three times. A two way ANOVA with replication was performed to test for effects of drain time and sieve. The results indicated neither effect was significant ($P > 0.05$).

When the sample size was increased from 15g to 45g, using the same experimental procedure and in particular, the same submerging time in the manure slurry as well as same draining time, WHC decreased compared to the smaller 15g sample size. WHC of corn cob with the addition of 8% TS_m manure slurry reduced to 4.3 ± 0.1 g of water per g of dry mixture. It was determined by some additional calculations of the percentages of total solids in the corn cob bedding, manure and mixture, that the soaking time used for bigger sample size was probably not sufficient to achieve an equilibrium value of WHC.

Soaking Time

For the 45g sample size, experiments were conducted to determine an appropriate longer soaking interval than the used for 15 g samples. The mixture soaking time was 45, 60, 75 and 90 min, 6, 18 and 24 h. It was found that WHC increased with longer soaking time and reached its maximum value after between 6 and the 18 h of soaking (Table 4.4 and Figure 4.2). A t-test for equal means (comparing the mean WHC value after 6 h of soaking in the manure slurry and the mean WHC value after 24 h of soaking) was conducted. No significant difference ($P > 0.05$) was found between 6 h and 24 h WHC. Additionally, the 6-h soaking time resulted in 98% of maximum (24 h) WHC. Thus, the selected soaking time for the determination of WHC with manure addition of corn cobs for 8% and 12% TS_m was 6 h.

Table 4.4 Water holding capacity (g of water per g of dry mixture) for varying percentages of manure total solids and for different soaking time (n=2 replications per soaking time) using 45g samples of corn cob media.

Soaking time	Manure TS_m	
	8%	12%
45min	4.4 (0.02) [a]	3.7 (0.15) [b]
60min	4.6 (0.09) [a]	3.6 (0.04) [b]
75min	4.3 (0.33) [a]	3.8 (0.10) [b]
90min	4.3 (0.34) [a]	3.7 (0.05) [b]
6h	5.2 (0.22) [a]	4.1 (0.07) [b]
18h	5.4 (0.00) [a]	4.2 (0.00) [b]
24h	5.3 (0.08) [a]	4.2 (0.07) [b]

Different lowercase letters within a row indicate significant differences among the TS_m of the same material ($P < 0.05$).

The effects on manure-bedding mixture WHC for varying percentages of manure total solids were identified. Preliminary results and conclusions when testing corn cob bedding WHC with manure addition are reported. WHC drops as the percentage of manure total solids increases (Figure 4.2). The baseline WHC of corn cob was 1.9 g of water per g of dry bedding and was significantly increased to a value of 5.2 g of water per g of dry mixture, with 8% TS_m manure slurry addition. Interestingly, for 12% TS_m manure, the WHC value was reduced by approximately 25% (to 4.1g of water per g of dry mixture). Even though WHC increases with manure addition, it appears to increase less when manure with higher TS_m content is added.

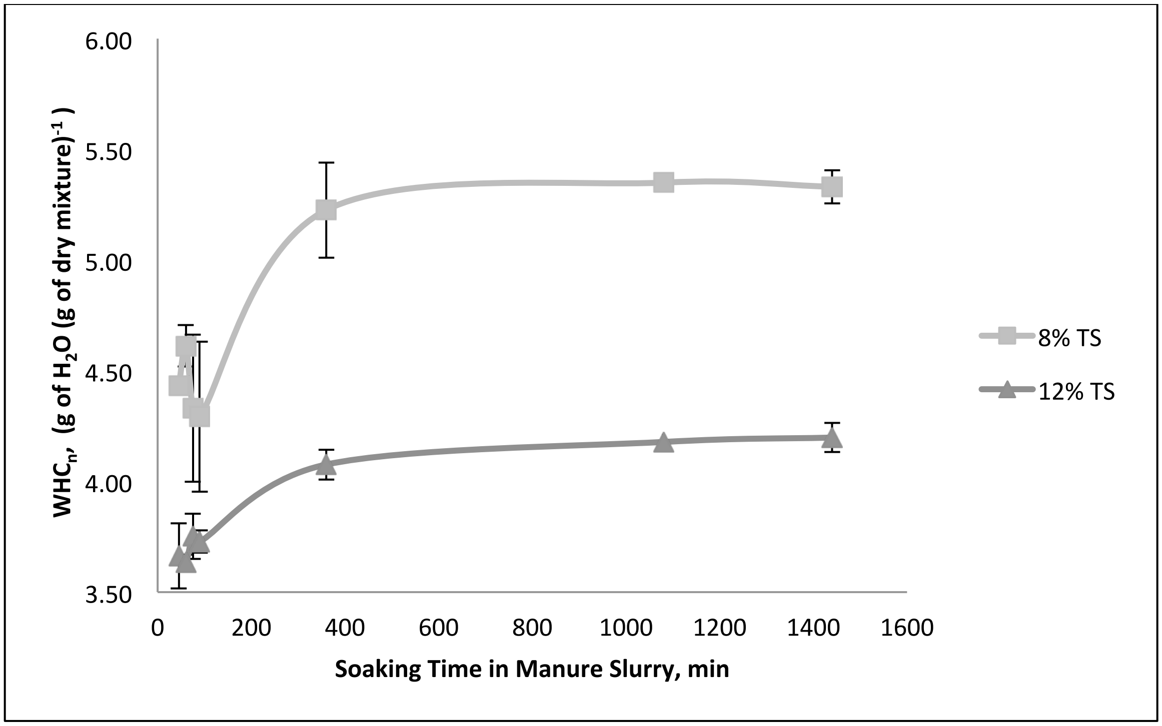

Figure 4.2 Water holding capacity (g of water per g of dry mixture) for varying percentages of manure total solids and for different soaking time.

Finally, the shortest time for immersing the bedding material in 8% and 12% TS_m manure slurry to determine the WHC value of corn cobs with manure addition was determined to be 6 h. After 6 h (24h) of soaking, WHC reached a mean value of about 98% of the maximum WHC value, and any differences were not statistically significant. This follows from a two sample t-test for equal means statistical analysis.

4.2.2 Determination of WHC

Bedding materials WHC when manure is added was determined. The reported values are the WHC normalized by manure (WHC_n, g H_2O (g dry mixture)$^{-1}$ using equation 5 as described in section 3.4.3) and the WHC expressed per unit mass of dry bedding only (WHC_b, g H_2O (g dry bedding)$^{-1}$ using equation 6). The WHC_n includes the dry mixture (manure and bedding) in the denominator and the WHC_b includes just the bedding.

The WHC values for the seven different bedding materials with manure addition (at 4%, 8%, 12%, 16% TS_m) are reported below in Table 4.5 are the normalized values for both a nominal manure TS_m content (4%, 8%, 12%, 16%) (WHC_n). Figure 4.3 is a different schematic giving the same information as Table 4.5. It shows how the WHC_n changes as manure TS_m increase. It is obvious that WHC is decreasing when manure with higher TS is added to the bedding.

Table 4.5 Mean (SD) values of WHC (g H_2O (g dry mixture)$^{-1}$) of bedding materials with manure addition at different manure TS_m contents (six to nine replications). Values are normalized to the specified manure total solids (WHC_n).

Bedding Material	4% TS_m	8% TS_m	12% TS_m	16% TS_m
Corn Cobs	4.6 (0.21) ^{a}	5.3 (0.19) ^{b}	4.1 (0.07) ^{c}	3.5 (0.45) ^{d}
Corn Stover	9.2 (0.28) ^{a}	6.7 (0.34) ^{b}	4.9 (0.21) ^{c}	3.7 (0.18) ^{d}
Pine Shavings	6.3 (0.29) ^{a}	5.7 (0.34) ^{b}	4.5 (0.11) ^{c}	3.4 (0.19) ^{d}
Switchgrass	6.6 (0.37) ^{a}	5.5 (0.60) ^{b}	4.3 (0.25) ^{c}	3.3 (0.28) ^{d}
Miscanthus	4.5 (069) ^{a}	4.8 (0.33) ^{a}	3.5 (0.45) ^{b}	2.8 (0.46) ^{c}
Wheat Straw	7.6 (0.29) ^{a}	6.0 (0.33) ^{b}	4.8 (0.35) ^{c}	3.5 (0.17) ^{d}
Soybean Stover	7.6 (0.21) ^{a}	5.5 (0.35) ^{b}	3.6 (0.47) ^{c}	2.6 (0.51) ^{d}

Different lowercase letters within a row indicate significant differences among the TS_m of the same material ($P < 0.05$).

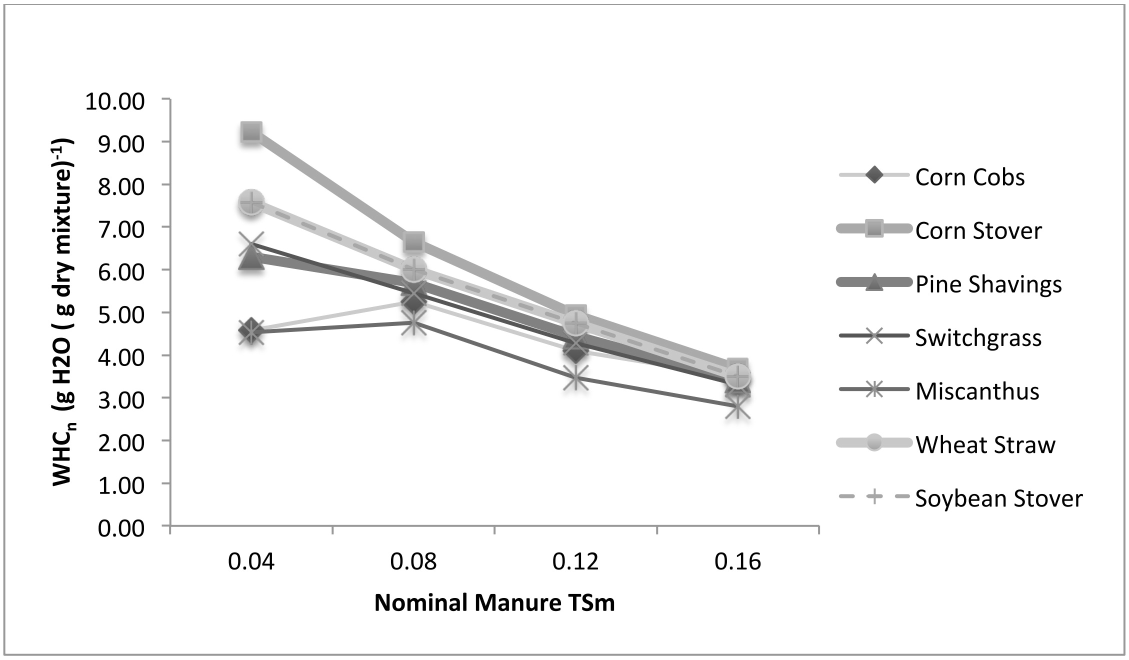

Figure 4.3 Changes in WHC_n as manure TS_m (nominal values) increase.

The results of these experiments indicate that bedding materials WHC increases when manure slurry, instead of just water, is added to the bedding (see Table 4.6 for baseline WHC). However, as manure TS_m increases, the WHC_n is reduced by a variable but substantial amount. All bedding materials WHC ranged from 2.6 to 9.2 g H_2O/g of dry mixture. These values were for soybean stover at 16% manure TS and corn stover at 4% manure TS, respectively. Within bedding materials, corn stover and soybean stover show the greatest variability, while corn cobs the least. For example, corn cobs WHC_n reduced from 4.6 to 3.5 g H_2O (g dry mixture)$^{-1}$ when TS_m increases from 4% to 16%, whereas soybean stover WHC_n reduced from 7.6 to 2.6 g H_2O (g dry mixture)$^{-1}$. The two factors that are potentially driving the within-bedding variability are the amount of water available in the manure and the manure mass. Within manure TS at 4% the variability is greatest among all manure TS used. As manure TS increased the variability reduced.

It seems that corn stover and wheat straw are the two bedding materials performing better than the rest of the bedding materials. For all manure TS_m their ability to hold water is greater than the other bedding materials. Corn stover and wheat straw have the highest WHC_n within that manure TS_m range. Pine shavings and soybean stover follow with higher WHC_n. Finally, the table illustrates all normalized WHCs for the same bedding material, are significantly different among manure TS, except for miscanthus at 4% and 8%.

4.3 Comparisons of WHC_b to the baseline WHC

WHC can also be expressed by bedding. As reported earlier in the Materials and Methods chapter the different WHCs presented in this work are the baseline WHC using just water, g H_2O (g dry bedding)$^{-1}$, the WHC_n normalized for a nominal manure TS_m content, g H_2O (g dry mixture)$^{-1}$ and the WHC_b expressed by bedding, g H_2O (g dry bedding)$^{-1}$. In this section the WHC_b will be discussed.

The baseline WHC by definition is equal to the mass of the water over the mass of the dry bedding. To make a direct comparison between the baseline WHC and the WHC when manure is added, both must be expressed with the same units in the denominator. Therefore, a comparison of the WHC_b to the baseline WHC wass done (Table 4.6 and Figure 4.4).

Table 4.6 Bedding materials baseline WHC and WHC_b at different manure TS_m contents (six to nine replications) – mean (SD).

Material	Baseline WHC	Manure Total Solids, TS_m			
		4%	8%TS_m	12%TS_m	4%
Corn Cobs	1.9 (0.01) ^{a}	4.2 (0.45) ^{b}	7.1 (0.34) ^{c}	7.2 (0.19) ^{c}	6.9 (0.48) ^{c}
Corn Stover	3.9 (0.09) ^{a}	11.0 (1.14) ^{b}	10.5 (1.69) ^{b}	10.3 (1.50) ^{b}	9.4 (1.43) ^{b}
Pine Shavings	2.2 (0.03) ^{a}	7.0 (0.56) ^{b}	9.6 (0.75) ^{c}	9.8 (0.66) ^{c}	7.6 (0.84) ^{d}
Switchgrass	1.9 (0.03) ^{a}	7.1 (0.54) ^{b}	10.0 (0.49) ^{c}	11.1 (0.93) ^{c}	6.5 (1.43) ^{d}
Miscanthus	1.2 (0.04) ^{a}	4.9 (0.58) ^{b}	11.8 (1.92) ^{c}	12.0 (0.23) ^{c}	6.8 (0.41) ^{d}
Wheat Straw	2.8 (0.06) ^{a}	8.9 (0.84) ^{b}	15.8 (1.31) ^{c}	16.3 (0.47) ^{c}	7.8 (1.09) ^{d}
Soybean Stover	2.6 (0.04) ^{a}	8.7 (0.66) ^{b}	11.7 (0.25) ^{c}	11.1 (0.18) ^{d}	6.1 (1.00) ^{e}

Different lowercase letters within a row indicate significant differences among the TS_m of the same material ($P < 0.05$).

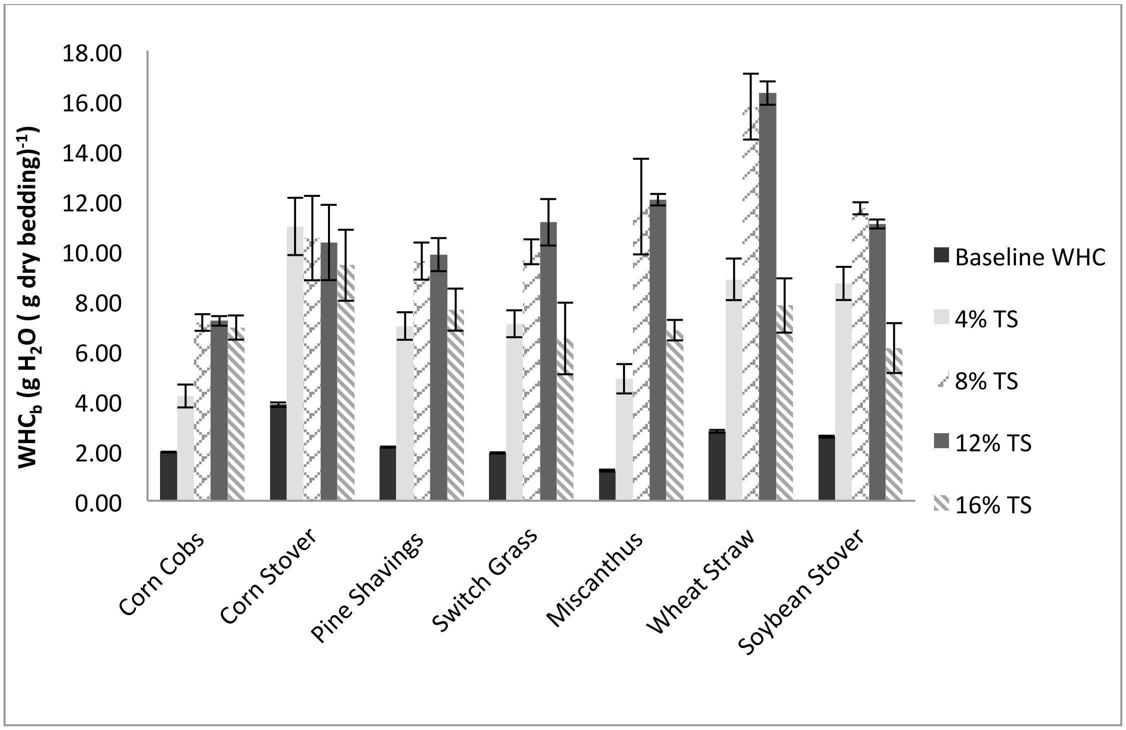

Figure 4.4 A schematic comparison of bedding materials baseline WHC and WHC_b (WHC using initial dry bedding in the denominator) at different manure total solids (TS_m) contents.

WHC_b with manure addition to corn cob media for 4%, 8%, 12% and 16% TS_m was 4.2 ± 0.45 (mean ± SD), 7.1 ± 0.34, 7.2 ± 0.19 and 6.9 ± 0.48 g of water per g of dry bedding, respectively (Table 4.6). These WHC_b values are significantly greater than the WHC of corn cob reported in literature and during our initial characterization of the bedding material. The percentage increase of corn cob bedding material's ability to hold water, when 4% TS_m manure was added, was more than 110% (Table 4.7). When 8% 12% and 16% TS_m manure was added, the WHC_b of corn cob is greater by approximately 260-270% than the initial WHC.

For corn stover, the WHC_b with 4%, 8%, 12% and 16% TS manure addition was 11.0 ± 1.14, 10.5 ± 1.69, 10.3 ± 1.50, 9.4 ± 1.43 g of water per g of dry bedding, respectively. All measured WHC_b were significantly greater than the baseline WHC corn stover. The percentage increase in corn stover bedding, when 4% TS_m manure was added, was more than 180%. Corn stover reacted differently than the rest of the materials for greater values of TS_m. Interestingly, when

8%, 12% and 16% TS_m was used, WHC_b was reduced, but it was still a significantly higher (by 150-170%) than the baseline WHC.

Pine shavings WHC increased from a baseline value of 2.2 ± 0.03 g of water per g of dry bedding, to 7.0 ± 0.56 g of water per g of dry bedding with 4% manure TS_m addition (225% above the baseline WHC), and up to 9.8 ± 0.66 with 12% (approximately 360% higher). Switchgrass, miscanthus and soybean stover have similar trends on how their WHC changes as manure Ts_m increase and appear to have the highest ability to hold liquid when 12% TS_m is added. Switchgrass reached 11.1 ± 0.93 g of water per g of dry bedding, miscanthus and soybean stover 12.0 ± 0.23 and 11.1 ± 0.18, respectively. Switchgrass reached a value that is 480% higher than the baseline WHC and soybean stover more than 330%. It is interesting that miscanthus WHC_b increased dramatically with manure addition, by almost 900% over its baseline value.

WHC_b with manure addition to wheat straw for 4%, 8%, 12% and 16% TS_m was 8.9 ± 0.84, 15.8 ± 1.31, 16.3 ± 0.47 and 7.8 ± 1.09 g of water per g of dry bedding, respectively (Table 4.6). These WHC values are significantly greater than the WHC of wheat straw reported in literature and during our initial characterization of the bedding material. Figure 4.5 illustrates the percent difference from the baseline WHC of the WHC_b values when manure in added at 4%, 8%, 12% and 16% TS. The percentage increase of wheat straw bedding material's ability to hold water, when 4% TS_m manure was added, was more than 220% (Table 4.7). When 8% 12% TS_m manure was added, the WHC of wheat straw is greater by approximately 330-350% than the initial WHC. Wheat straw is the bedding material with the greatest WHC_b when 8% and 12% manure TS_m is added.

Table 4.7 Percent difference of WHC_b from the baseline WHC for each bedding material (six to nine replications).

Bedding Materials	Increase in WHC_b over baseline WHC (water only)			
	4% TS_m	8% TS_m	12% TS_m	16% TS_m
Corn Cobs	115%	267%	270%	257%
Corn Stover	185%	173%	168%	145%
Pine Shavings	225%	345%	358%	255%
Switchgrass	269%	419%	481%	239%
Miscanthus	304%	874%	896%	464%
Wheat Straw	219%	467%	487%	181%
Soybean Stover	238%	355%	331%	137%

The results of this study show that miscanthus, wheat straw and switchgrass had the largest increases in WHC_b over baseline when manure was added. Conversely, corn stover's WHC_b, while greater than the baseline, was lower than any other bedding materials despite having a baseline WHC that is the highest of all.

The trend line of the WHC followed by all bedding materials is the similar. WHC_b values of the bedding materials tested, for all of manure TS contents used, are significantly greater than the respective baseline WHCs without manure addition. Most of the bedding materials WHC_b are higher at 8% than at 4%TS_m (except corn stover) and as manure TS increased above 8%, the percentage difference from the baseline WHC dropped. Interestingly, when 4% and 16% TS manure was used, the WHC values were reduced in comparison to the other two manure total solids content but they were still substantially greater than the baseline WHCs.

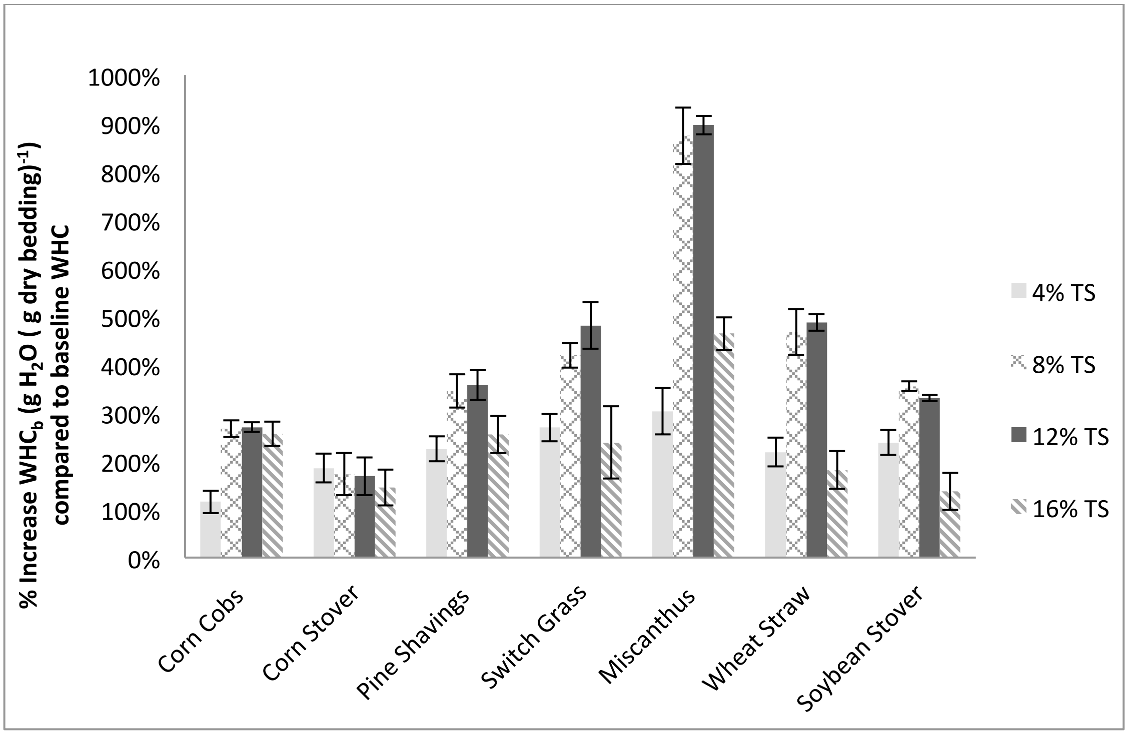

Figure 4.5 Percent difference in WHC_b over the baseline WHC value for manure added at 4%, 8%, 12% and 16% TS.

The graph below (Figure 4.6) is a different schematic giving the same information as Figure 4.4. It shows how the WHC_b changes as manure TS_m increases. It is obvious that WHC is increasing when manure is added to the bedding instead of water. Additionally to Figure 4.4, this graph gives one more interesting bit of information. There is plateau noticed on the WHC between 8% and 12% manure total solids. This shows that the WHC remains almost unchanged when either 8% TS_m or 12% is used. A t-test for equal means was performed between the mean WHC_b values for the two manure total solids contents. At $\alpha=0.05$ level of significance, no significant difference existed between the two means. Bedding materials WHC_b seem to reach equilibrium between the two manure TS contents, which is potentially driven by the amount of free water available in manure and the mass of the manure.

This finding is extremely valuable for livestock producers willing to construct a BPS in Illinois. Feces and urine produced by beef cattle are generally accepted to have approximately 8% to 12% total solids content (ASABE D384. 2, 2005). Thus, when designing a BPS in Illinois the design criteria: the amount of bedding needed to be added and the total storage volume requirements do not need to be calculated for both 8% TS_m and 12% for all the methods. For instance when calculating the total storage volume with the MWPS-18 Method 2, the pooled WHC_b value for a particular bedding can be used.

In this figure (Figure 4.6) the WHC_b shows a quadratic effect as manure TS increase, in comparison to Figure 4.3, where the WHC_n is linear.

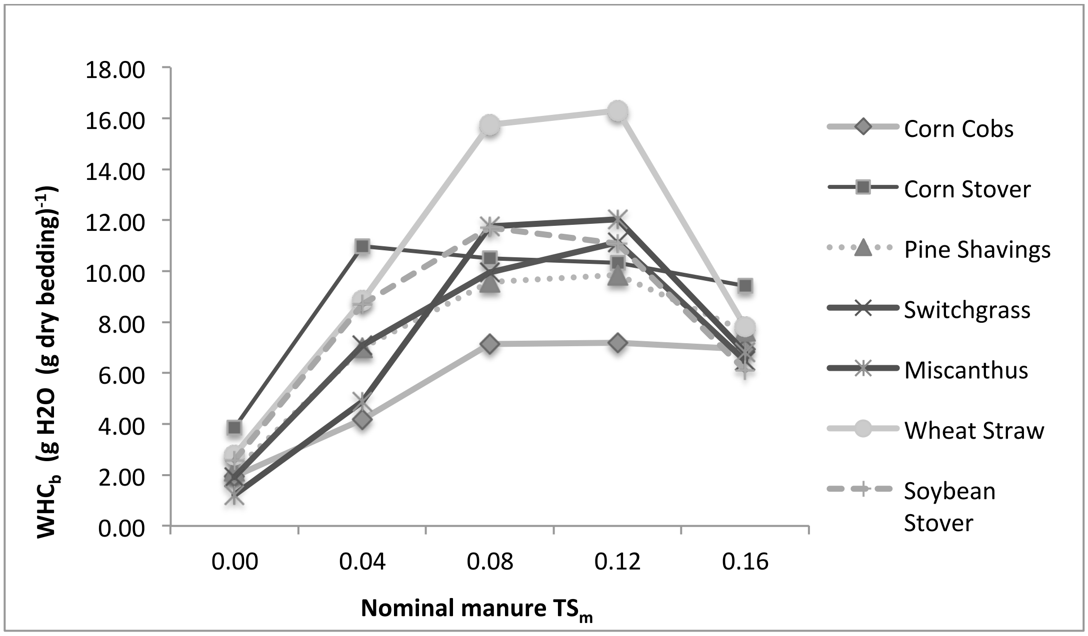

Figure 4.6 Changes in WHC_b as manure TS_m (nominal values) increase.

Another important finding relates to the manure-bedding mixture TS (TS_{mix}) at saturation. Table 4.6 and Figure 4.7 present these values. TS_{mix} at saturation ranges between 12.0% when 4% TS_m is added to the bedding to 27.7% when 16% TS_m is added. It is obvious that TS_{mix} increases when manure with higher total solids content is added. The final dry matter of the mixture is lower as WHC_b gets higher.

Table 4.8 Manure - Bedding mixture TS (TS_{mix} (%)) at different manure TS_m contents (six to nine replications) – mean (SD).

Bedding Material	4% TS_m	8% TS_m	12% TS_m	16% TS_m
Corn Cobs	22.0 (1.10) [a]	17.3 (0.89) [b]	20.5 (0.53) [c]	22.3 (0.52) [d]
Corn Stover	12.0 (0.63) [a]	14.0 (0.89) [b]	16.7 (0.82) [c]	20.3 (0.52) [d]
Pine Shavings	17.2 (0.75) [a]	14.7 (0.52) [b]	16.3 (0.52) [c]	22.5 (1.05) [d]
Switchgrass	16.3 (0.70) [a]	16.2 (0.50) [a]	18.2 (0.79) [b]	22.6 (0.99) [c]
Miscanthus	22.3 (2.27) [a]	18.5 (1.37) [b]	21.7 (2.44) [c]	26.1 (4.13) [d]
Wheat Straw	14.5 (0.41) [a]	14.2 (1.09) [a]	17.2 (1.49) [b]	22.1 (1.39) [c]
Soybean Stover	14.5 (0.31) [a]	16.3 (1.86) [b]	20.9 (2.51) [c]	27.7 (4.52) [d]

Different lowercase letters within a row indicate significant differences among the TS_m of the same material ($P < 0.05$).

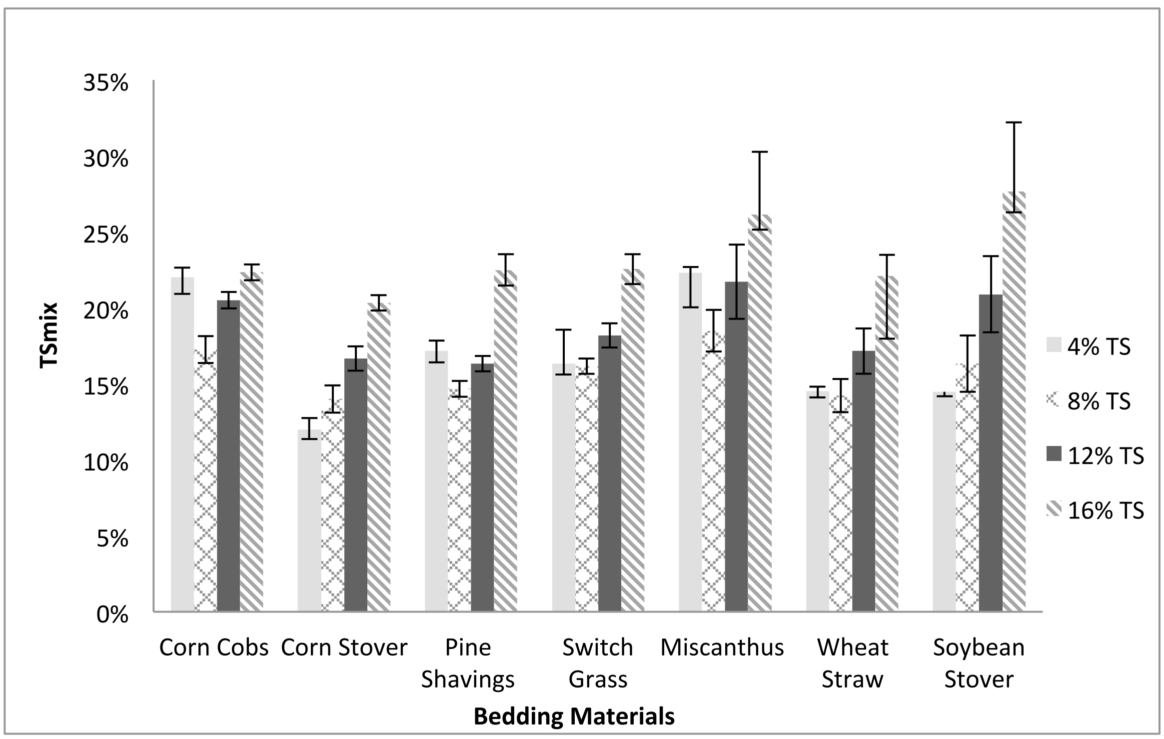

Figure 4.7 Manure - Bedding mixture TS (TS_{mix}) at different manure TS_m contents (error bar: SD).

Finally, some additional calculations were done to test if manure is accumulated or lost during the experimental process. Assuming that the initial mass of the bedding material used for the experiments was maintained, it was proven that manure accumulated during the soaking process for 4% TS_m. Graph 4.6 shows that all bedding materials, except corn and soybean stover, have higher manure-bedding mixture TS (TS_{mix}) at saturation at 4% than at 8% TS_m. An explanation to why this is happening is the manure solids settling rates over time. At 4%TS_m solids are settling faster than at higher TS_m.

Earlier in this chapter the different WHCs were discussed. The reported values are the WHC normalized by manure (WHC_n, g H_2O (g dry mixture)$^{-1}$) and the WHC expressed per unit mass of dry bedding only (WHC_b, g H_2O (g dry bedding)$^{-1}$). In practice WHC_b should be used. In order to make direct comparisons between the baseline WHC and the WHC when manure is added, both must be expressed with the same units in the denominator. The baseline WHC by definition is equal to the mass of the water over the mass of the dry bedding. The WHC_n includes the dry mixture (manure and bedding) in the denominator while the WHC_b includes just the bedding. Additionally, to be able to calculate the total storage volume using the existing methodologies the units of the WHC used should be g H_2O (g dry bedding)$^{-1}$.

4.4 Implications and Limitations of Research

Beef cattle housing systems have a substantial impact on the overall health and welfare of the animals and financially affect the industry. BPSs are an environmentally and economically sound alternative for housing, as well as an effective animal manure system. The bedding material is the basic component of these systems.

The results of this study have substantial implications on BPS design, specifically bedding volume requirements. Bedding materials seem to improve their physical properties, increasing their WHCs, with manure addition. WHC is an essential parameter for selecting a bedding material. From one point of view the greater the WHC, the less bedding material is needed for the same amount of manure. Another consideration is that materials that absorb too much water or urine are not suitable as bedding material. This high moisture content can rupture the cell walls which potentially causing additional free water. Moreover wet bedding also contributes to dirtier cattle.

In practice, these results are very important for livestock producers who are willing to construct and utilize a solid manure bed pack system in Illinois. The goal is to help livestock producers to decide what media(s) works best for their purpose and probably expand the number of alternative media that could be potentially more economically used in bedded pack systems.

With the information in this research, livestock producers can compare several material's WHC, and to more accurately determine the type of bedding material(s) most appropriate to their design. They can also estimate the volume of each type of bedding required, and thus, the total storage volume needed. Current methods that estimate the total storage volume for solid manure BPS illustrated that a bedded pack barn constructed in Illinois needs to be three times the size of one built in a neighbor state for the same number of animals (Pepple and Gates 2013). Subsequently, if producers know how to better manage the bedding material both capital and operation expenditures for a barn of could be decreased. Using the data from this research and the methods mentioned above it has been shown that the amount of bedding needed in a BPS is less than what is currently estimated.

4.4.1 Bedding Material Selection

Based on the findings of this research on the WHCs and the TS content of the manure-bedding saturated mixtures, the availability in the Midwest and cost effectiveness of these seven bedding materials, corn stover and wheat straw are recommended for use in a BPS in Illinois. Wheat straw was the best performing bedding material. Corn stover, even though performing similarly to pine shavings, miscanthus and soybean stover, is chosen because it is available in the broader Illinois area and is relatively cheap to be supplied with.

4.4.2 Amount of Bedding Needed - Total Storage Volume Required

MWPS-18 Method 1

Using the first method from MWPS-18 (2000), the amount of bedding needed and the total storage volume required were estimated. Currently, the method suggests 6.6 kg $hd^{-1}d^{-1}$ of bedding are required, when 8% TS_m is used, to achieve a final bed pack total solids content (TS_{mix}) of 25% and a total storage volume of 0.064 m^3 $hd^{-1}d^{-1}$ (Pepple and Gates 2013). Comparing the ratio of the manure produced per animal and day (29.1 kg per head per day) to the mass of the bedding currently required, to the manure-bedding mass ratio as recorded from the experiments, it was noticed there is a direct relationship of this ratio to the WHC_b. The manure-bedding ratio was 4.4 when 8% manure TS_m were used and 5.8 with 12% TS_m. Using the experimental data it was proven that the ratio for each bedding material and manure TS_m was equal to the respective WHC_b. This is a very interesting finding, as it shows that currently in Illinois it is assumed that the WHC of the bedding materials used in BPS is 4.4 – 5.8 g of water (g of dry bedding)$^{-1}$. The results of this investigation indicated that the WHC values are much higher than the ones currently assumed. This means that the bedding mass and volume recommendations are also different, as shown below.

In Table 4.9 the total storage volume needed in a BPS is calculated for each of the bedding materials tested, using the experimental data (bulk density of each bedding material) and assuming that the manure produced by the animals is at 8% to 12% TS_m. The total amount of bedding required was determined using Figure 3.1 (in section 3.5.1) which was based on MWPS-18 and updated by Pepple and Gates (2013) for current manure production standards. The daily bedding requirements were estimated for each manure TS content, for instance 8%, following TS curve in Figure 3.1 until it intersects the desired bed pack dry matter (25%). From that point a vertical line to the x-axis will indicate the mass of bedding needed. 6.6 and 5.0 kg $hd^{-1}d^{-1}$ of bedding is needed when 8% and 12% TS_m is used, respectively. The required volume of the bedding is then this mass of the bedding over its bulk density.

Table 4.9 Total storage volume requirements for BPS as calculated using the MWPS-18 Method 1, amount of bedding 6.6 and 5.0 kg $hd^{-1}d^{-1}$ (and volume 0.064 $m^3hd^{-1}d^{-1}$) for 8% and 12% TS_m, respectively and the bulk density of each bedding material from this research work.

Bedding Material	Bulk Density (kg m^{-3})	Total Storage Volume ($m^3hd^{-1}d^{-1}$)	
		8% Manure TS_m Bedding Required (6.6 kg $hd^{-1}d^{-1}$)	12% Manure TS_m Bedding Required (5.0 kg $hd^{-1}d^{-1}$)
Corn Cobs	216.5	0.030	0.023
Corn Stover	39.3	0.168	0.127
Pine Shavings	64.6	0.102	0.077
Switchgrass	77.5	0.085	0.065
Miscanthus	32	0.206	0.156
Wheat Straw	24.3	0.272	0.206
Soybean Stover	64.8	0.102	0.077

For the first method, the desired final manure-bedding mixture total solids were 25%. The experiments showed that TS_{mix} did not reach 25%; instead it was equal to 14% and 17% for 8% and 12% manure TS_m, respectively. The amount of bedding was manipulated for the calculations so the TS_{mix} was equal or greater than 25%. The difference in the final manure-bedding mixture total solids was because during the experiments there were no evaporation losses. Table 4.10 presents the amount of bedding and total storage volume requirements for BPS as calculated using the MWPS-18 Method 1 and the data collected from this research work.

The amount of supplemental bedding required varies from 4.0 to 6.4 kg $hd^{-1}d^{-1}$, depending on the bedding material type and the manure total solids. This is less than the 6.6 and 5.0 kg $h^{-1}d^{-1}$ of bedding currently suggested for 8% and 12% TS_m, respectively. However, the total storage requirements are not always lower than the calculations by Pepple and Gates (2013). For instance, corn stover, pine shavings, miscanthus, wheat straw and soybean stover showed higher storage requirements. This is due to the differences in bedding material's bulk densities. The method as used by Pepple and Gates assumed the bedding bulk density was 96.1 kg m^{-3}, regardless of the bedding type, or its particle size distribution.

Table 4.10 Bedding and total storage volume requirements for BPS as calculated using the MWPS-18 Method 1 and the data collected from this research work.

Bedding Material	8% Manure TS_m		12% Manure TS_m	
	Bedding Required (kg $h^{-1}d^{-1}$)	Total Storage Volume ($m^3h^{-1}d^{-1}$)	Bedding Required (kg $h^{-1}d^{-1}$)	Total Storage Volume ($m^3h^{-1}d^{-1}$)
Corn Cobs	6.4	0.030	5.2	0.024
Corn Stover	6.1	0.156	5.2	0.133
Pine Shavings	6.1	0.095	5.5	0.085
Switchgrass	5.9	0.076	4.4	0.057
Miscanthus	4.8	0.149	4.0	0.124
Wheat Straw	5.4	0.222	4.4	0.181
Soybean Stover	5.8	0.090	4.5	0.069

MWPS-18 Method 2

To apply these new data to MWPS-18 Method 2, the pooled mean WHC_b value for 8% and 12% TS_m, was used for each bedding material, since it was proven that there is no significant difference on the WHC_b between 8% TS_m and 12%. The MC_m used in the equation was 90% (the mean value for 8% and 12% manure total solids). Total bedding required per animal per day as calculated by Pepple and Gates (2013) ranged from 1.9 to 3.0 kg; however, the new data show tremendously different bedding recommendations: 0.4 – 0.9 kg $hd^{-1}d^{-1}$. Table 4.11 presents each bedding material's bedding mass – volume requirements.

Table 4.11 Bedding and total storage volume requirements for BPS as calculated using the MWPS-18 Method 2.

Bedding Material	Bedding Required (kg $hd^{-1}d^{-1}$)	Total Storage Volume ($m^3hd^{-1}d^{-1}$)
Corn Cobs	0.9	0.032
Corn Stover	0.6	0.037
Pine Shavings	0.7	0.035
Switchgrass	0.6	0.033
Miscanthus	0.6	0.038
Wheat Straw	0.4	0.038
Soybean Stover	0.6	0.034

These values in Table 4.11 are very sensitive to the WHC values. As the WHC_b is much higher than the baseline WHC of these bedding materials the amount of bedding needed is significantly decreased. This method neglects evaporation losses within the system; however, it accounts for a fixed (25%) percentage of free water absorbed by the bedding. During the experiments, evaporation was prevented; thus, the final bed pack total solids were less than 25%. Nevertheless, if evaporation is naturally occurring then the TS_{mix} would be greater and probably closer to the 25% currently required in Illinois.

South Dakota NRCS Method 3

South Dakota NCRS method assumes evaporation losses occur within the barn and the bed pack remains dryer without using extra bedding. The table below includes the ranges for the total storage volume required in BPS, assuming 8% and 12% TS_m manure is added to the bedding.

Table 4.12 Total storage volume requirements for BPS as calculated using the South Dakota NRCS Method.

Bedding Material	Total Storage Volume ($m^3 hd^{-1} d^{-1}$)	
	Hoop Structures	Monoslope Buildings
Corn Cobs	0.030	0.032
Corn Stover	0.037	0.039
Pine Shavings	0.037	0.039
Switchgrass	0.033	0.036
Miscanthus	0.028	0.031
Wheat Straw	0.037	0.039
Soybean Stover	0.031	0.033

The total storage volume requirements are substantially higher than the ones calculated before by Pepple and Gates (2013) (0.016-0.017 m^3 $hd^{-1}d^{-1}$). The final manure-bedding mixture total solids used for these calculations ranged between 14% and 28%, much lower than the 32% used before. During the experimental procedures there were no evaporation losses occurring. This is an important limitation of the present research work. The South Dakota NRCS Method assumes that substantial evaporation is naturally occurring within the barn. As it is shown by a bedded pack nutrient analysis, a realistic percentage for final bed pack total solids is 30%-40%– see Appendix C.

4.4.3 Comparisons and discussions on the three methods

A comparison of these three total storage volume estimation methods showed significantly different total storage volume recommendations. The amount of bedding required daily per animal ranged from 0.4 to 6.6 kg (0.9 to 14.5 lb). Total storage volume estimates ranged from 0.023 to 0.272 m^3 (0.8 to 9.6 ft^3) per animal per day. The MWPS-18 Method 1,which is the method currently used in Illinois, yielded daily bedding requirements ranging from 4.0 to 6.4 kg $hd^{-1}d^{-1}$ for miscanthus-12%TS_m and for corn cobs-8% manure TS_m, respectively. 6.6 kg $hd^{-1}d^{-1}$

was calculated by Pepple and Gates (2013) using the same method with assumptions. The volume production was estimated between 0.024 $m^3\ hd^{-1}d^{-1}$ (for corn cob bedding and 12% TS_m) to 0.222 $m^3\ hd^{-1}d^{-1}$ (for wheat straw bedding and 8% TS_m). Pepple and Gates (2013) had estimated the volume production was equal to 0.064 $m^3\ hd^{-1}d^{-1}$. The variations in the total storage volume requirements are caused by the differences in bedding materials bulk density.

For the second MWPS-18 method, using the new values for WHC_b, the daily bedding requirements ranged from 0.4 to 0.9 kg $hd^{-1}d^{-1}$, substantially lower than amount obtained using Method 1. The amount of bedding required and the total storage volume needed are less than what Pepple and Gates (2013) calculated. However, using the South Dakota NRCS Method 3 greater total storage volume requirements were suggested than what Pepple and Gates (2013) did. This is likely due to that South Dakota NRCS Method assumes that substantial evaporation is naturally occurring within the barn while during this research evaporation losses were prevented.

Comparison of current mass and volume recommendations, estimated in this study and those made by Pepple and Gates (2013), showed significant differences. For the first method differences in total storage volume recommendations are due to material's bulk density. For MWPS-18 Method 2 differences in the amount of bedding needed are due to WHC_b and finally for South Dakota NRCS Method the evaporation losses from the bed pack and the final TS_{mix} are causing the total storage volume differences. To understand the substantially different recommendations corn stover is used as an example.

Table 4.13 Corn Stover: Comparison of the bedding mass needed per head per day among the three methods.

<table>
<tr><td colspan="7">Bedding Mass Required, kg $hd^{-1}d^{-1}$</td></tr>
<tr><td></td><td colspan="2">MWPS-18
Method 1</td><td colspan="2">MWPS-18
Method 2</td><td colspan="2">SD NRCS
Method 3</td></tr>
<tr><td>Bedding Material</td><td>This study</td><td>Pepple and Gates (2013)</td><td>This study</td><td>Pepple and Gates (2013)</td><td>This study</td><td>Pepple and Gates (2013)</td></tr>
<tr><td rowspan="2">Corn Stover</td><td rowspan="2">6.6</td><td rowspan="2">6.6</td><td rowspan="2">0.6</td><td rowspan="2">1.9</td><td colspan="2">2.4 [h]</td></tr>
<tr><td colspan="2">2.8 [m]</td></tr>
</table>

[h] Hoop Structure, [m] Monoslope Building

Table 4.13 shows a comparison of the corn stover bedding mass needed per head per day among the three methods. The MWPS-18 Method 1. This method suggests the amount of bedding needed in a BPS in Illinois is 6.6 kg $hd^{-1}d^{-1}$. For this method there were no difference in the findings of this research on how much bedding is needed. However, for the second method, this was not the case, because when manure is added WHC_b numbers increase. The amount of bedding needed is significantly lower than what Pepple and Gates (2013) estimated based on baseline WHC reported in literature. The third method is a rule of thumb given to producers, thus there is no difference in bedding mass recommendations.

Table 4.14 Corn Stover: Comparison among the three methods on how much total storage volume is required (m^3 per 1000 head per day).

Total Storage Volume (m^3 1000 $hd^{-1}d^{-1}$)*						
	MWPS-18 Method 1		MWPS-18 Method 2		SD NRCS Method 3	
Bedding Material	This study	Pepple and Gates (2013)	This study	Pepple and Gates (2013)	This study	Pepple and Gates (2013)
Corn Stover	168	64	37	39	36 [h]	16 [h]
					39 [m]	17 [m]

[h] Hoop Structure, [m] Monoslope Building

*Per 1000 animals

Table 4.14 shows the comparisons among the three methods on how much total storage volume for corn stover bedding material is required in m^3 per 1000 head per day. Currently, in Illinois producers are required to provide 64 m^3 of storage base per 1000 head per day (MWPS-18 Method 1). However, when the bulk density that was measured from this study was used, this was increased drastically to 168 m^3 1000 $hd^{-1}d^{-1}$. So there is a substantial difference for the first method.

There is no significant difference in total storage volume between what is recommended by Pepple and Gates and for MWPS-18 Method 2. The increased WHC_b and the bedding materials bulk densities as measured during this study were used. However, Pepple and Gates did not use bulk densities specific to the bedding materials, instead a bulk density of 96.1 kg m^{-3} was assumed for all beddings.

Using the SD NRCS method Pepple and Gates estimated 16 and 17 m^3 1000 $hd^{-1}d^{-1}$, while the numbers of this research are higher (36 and 39 for hoop and monoslope buildings, respectively). The South Dakota method estimated the bed pack density, the moisture content and thus the final bed pack TS, which was equal to 31.9%. During this study the final manure-bedding mixture TS were 14% to 28%, substantially lower than what South Dakota assumed. This is why the recommendations of this study are higher. The other assumption made is the pack density, which was not evaluated during this study.

A BP facility was visited and bed pack samples were collected and tested for their final dry mater, which was 32.8%– see Appendix C. Using this number the total storage volume decreases (15 and 20 for hoop and monoslope buildings, respectively) and the values are comparable to what South Dakota estimated. Based on those numbers, the assumptions that are made by South Dakota NRCS on bed pack are similar to what producers are experiencing in Illinois. However, additional research should be done to verify that this is accurate for the climate in Illinois.

CHAPTER 5. SUMMARY AND CONCLUSIONS

5.1 Conclusions

A characterization of seven different biomass types which can be used as bedding materials for deep-bedded barns was done in this study. The characterization included the determination of particle size distribution, bulk density, and effect of four different TS manure mixtures on WHC of the bedding materials. The results of this effort were used to compare three different methods for estimating bedding mass and manure-bedding mixture volume storage requirements for BPS beef facilities.

This research showed that baseline WHC of the majority of these seven bedding materials fall within the ranges found in the literature. Miscanthus, has not been previously evaluated. An SOP for measuring WHC with manure addition was developed. Based on the results of this study, WHC_n increased significantly with manure addition. This increase was greatest for 8% and 12% manure TS_m. Interestingly, when 4% and 16% TS manure was used, the WHC_n values were reduced in comparison to the 8% and 12% TS, but they were still substantially greater than baseline WHC. All bedding materials WHC_n ranged from 2.4 to 8.8 g H_2O (g of dry mixture)$^{-1}$. These values were for soybean stover at 16% manure TS and corn stover at 4% manure TS, respectively. Furthermore, no significant difference in the WHC_b between 8% and 12% manure total solids was found. This finding is valuable for livestock producers willing to construct a BPS, since feces and urine produced by beef cattle are generally assumed to have between 8% and 12% total solids content.

Based on the findings of this research, and the availability and cost effectiveness of these seven bedding materials, corn stover and wheat straw are recommended for use in as bedding in Illinois BPS. These two bedding materials perform well, but most importantly are available in the broader Illinois area and they are relatively inexpensive.

Using corn stover and wheat straw a comparison of three design methods to estimate amount of bedding required and total storage volumes for BPS showed significantly different volume recommendations, with both higher and lower values than was previously reported. Total bedding required per animal per day ranged from 0.6 to 6.6 kg for these three design methods using the updated values for WHC and bulk density from this study. Compared to current bedding recommendations in Illinois (6.6 kg $h^{-1}d^{-1}$), the MWPS-18 Method 2 and SD NRCS Method 3 suggested 90% and 60% lower amounts of bedding, respectively. Daily volume production estimates for 1000 head ranged from 16 to 168 m^3. Substantially more total storage volume than what currently recommended (64 m^3) is needed according to Method 1 (160%), while approximately 40% and 70% less is estimated to be needed using Methods 2 and 3, respectively.

5.2 Recommendations for Future Research

There are still no data available to indicate the levels of evaporation losses that occur from the bed pack. This is a challenging research problem, because evaporation depends on numerous uncontrolled factors including specific bedding material, its characteristics (initial moisture content, bulk density, particle size distribution), climate, building design, and animal stocking density. Additionally, the bulk density of the bed pack in the laboratory and the barn can be substantially different due to differences in moisture content, bedding compaction that is caused by the animals and, of course, characteristics of the bedding material itself. In the lab the bed pack bulk density is homogeneous, something that generally cannot happen in a barn. Thus, generalization of these findings must be done with some caution. Some other limitations of this work include the fact that the WHC is, by definition, the moisture content (wet basis) at saturation. In practice, there should be a safety factor considered, so that BPS moisture content is lower than in the lab. Finally, the majority of the bedding materials went through a 1” screen, which might not be appropriate for commercial use.

Potential future work is recommended to include the determination of the effects of naturally occurring evaporation losses within the system on bed pack dry matter content and the examination of the seepage from the bed pack. Finally, research is needed to test if bed pack characteristics vary by region and climate in order to improve the design methodology.

APPENDIX A: TOTAL SOLIDS TEST

APHA Standard Method SM 2540 B

Summary of Test Method

The TS of bedding or manure slurry were determined according to the Standard Method 2540B for total solids (SM 2540B 1998; APHA, AWWA, and WEF 2012). Total solids are expressed as a percentage.

Apparatus

- Electronic gram scale or balance scale with a minimum of 0.1 mg resolution.
- Small aluminum containers.
- Drying oven set at 103 – 105 °C.
- Glass desiccators.

Sampling and Testing Specimens

1. Always handle containers with gloves on.
2. Prepare specimen by separating the sample of bedding from a bag or bale taking 1/3 from the top, 1/3 from the middle and 1/3 from the bottom of the bag.
3. Thoroughly mix manure sample before using it. Manure should be at room temperature.

Procedure

1. Measure and record the weight of each aluminum container, using the balance
2. Place about 10-15 g of well mixed bedding or manure sample in a pre-weighed container.
3. Measure and record the weight of the wet sample and container.
4. Place sample in the oven at at 103 – 105 °C for 24 h.
5. Remove sample from oven and cool to room temperature in glass desiccator for 1-2 h.

6. Measure and record the final weight of dry sample and container.

7. Do it triplicate.

The TS content of the bedding material is calculated as follows:

$$TS = \frac{M_{dm}}{M_T} \qquad (1)$$

where,

TS = Total Solids, *g dry matter (g wet sample)*$^{-1}$

M_{dm} = Mass of Dry Matter, g

M_T = Total Mass of Wet Quantity, g

Report

- Report the percent of TS in the sample.
- Report average and standard deviation.

APPENDIX B: STANDARD OPERATING PROCEDURE FOR MEASURING BEDDING-MANURE WHC

Summary of Test Method

Product specimen should be conditioned and weighed when saturated and re-weighed when dry to determine bedding material water holding capacity with manure addition. The water holding capacity is expressed as g of water per g of dry mixture (manure – bedding). It can also be expressed per gram of dry bedding too.

Apparatus

- ASTM E11 no. 8 test sieve, 203.2 mm (8 in.) diameter.
- ASTM E11 no. 8 test sieve pan, 203.2 mm (8 in.) diameter.
- ASTM E11 no. 8 test sieve leads, 203.2 mm (8 in.) diameter or plastic wrap.
- Large mixing bowl 5.5 L capacity.
- Electronic gram scale or balance scale with a minimum of 0.0001 g resolution.
- Spatula.
- Large bowl for the soaking phase.
- Small aluminum containers.
- KitchenAid mixer (Classic Plus) with dough kneader attachment capable of 60 to 90 rpm on low setting (low rpm should be used to minimize damage to fibers).
- Drying oven set at 103 – 105 °C.
- Glass desiccators.

Sampling and Testing Specimens

1. Always handle containers with gloves on.
2. Prepare specimen by separating the sample of bedding from a bag or bale taking 1/3 from the top, 1/3 from the middle and 1/3 from the bottom of the bag.
3. Thoroughly mix manure sample before using it. Manure should be at room temperature.

Procedure

The ASTM D7367 – 07 Standard Method for the determination of WHC was used as a basis for determining the WHC for manure – bedding mixtures, but minor modifications were introduced. The procedure developed in this research is as follows:

1. Weigh mixing bowl and place 45 g of bedding material, in mixing bowl.
2. Add manure slurry of known TS at room temperature (23°C ± 2°C (73°F ± 4°F)) to the bowl.
3. Blend for 5 min with kitchen mixer at low setting (using a dough kneader or a hook).
4. Remove with a spatula and place the bowl contents, the mixture, in a sieve with pan underneath.
5. Remove any remaining bedding and manure particles or manure from the bowl and the mixing attachment with the spatula and add them to the mixture on the sieve (ASTM E11 no. 8 test sieve, Dual Manufacturing Co, Franklin Park, IL, USA).
6. Using the spatula, distribute mixture evenly across the sieve screen surface.
7. Place sieve in the large bowl containing enough manure slurry of the same (known) TS content (4%, 8%, 12%, 16%) to saturate specimen without overflowing the sieve.
8. Leave specimen in sieve to soak for at least 6 h.
9. Use lid or plastic wrap to cover the sieve to prevent from evaporation loses during the soaking process.
10. Slowly remove sieve of saturated mixture from the manure slurry and place it on the pan.
11. Let the sample rest horizontally (covered) for 5 min.
12. Allow the sample to drain at 20-30° angle for 10 min (covered).
13. Measure the weight of the sieve with the saturated sample.
14. Take three subsamples from the saturated mixture and place them in pre-weighed small aluminum containers.
15. Record the total weigh of the aluminum container and saturated mixture subsample to the nearest 0.1 mg.

16. Place the subsamples in the oven at 103 – 105 °C for 24 h until completely dry.
17. Remove them from the oven and place them immediately into glass desiccators for 2-3 h to cool down to room temperature.
18. Record the weight of the container and the dry sample.
19. Calculate the WHC with manure mixture with the following equation:

WHCs with manure addition was calculated using the following formula:

$$WHC_{mix} = = \frac{M_{mix,wb}}{M_{mix,db}}$$

where:

WHC_{mix}= Manure-Bedding Mixture Water Holding Capacity, g H_2O (g dry mixture)$^{-1}$

$M_{mix,wb}$ = Mass of the Manure-Bedding Mixture at Saturation (wet basis), g H_2O

$M_{mix,db}$ = Mass of Dry Manure-Bedding Mixture, g

Finally, WHC can also be expressed per unit of dry bedding (WHC_b):

$$WHC_b = = \frac{M_{mix,wb}}{M_{b,db}}$$

where:

WHC_b= Manure-Bedding Mixture WHC Expressed by dry matter, g H_2O (g dry bedding)$^{-1}$

$M_{mix,wb}$ = Mass of the Manure-Bedding Mixture at Saturation (wet basis), g H_2O

$M_{b,db}$ = Mass of Dry Bedding, g

Report

- Report the water holding capacity as g of water per g of dry mixture or per dry bedding.
- Report average and standard deviation.

APPENDIX C: BEDDED PACK NUTRIENT ANALYSIS

Midwest Laboratories, Inc.

13611 B Street Omaha, Nebraska 68144-3693 (402) 334-7770 FAX (402) 334-9121 www.midwestlabs.com

Lab # 2322601	**Report of Analysis**	Report Number: 14-274-4076
Account: 21565	LAURA PEPPLE STE 332 UNIVERSITY OF ILLINOIS 1304 W PENNSYLVANIA AVE URBANA IL 61801	Robert Ferris Client Service Representative 402-829-9871
Date Sampled: **Date Received:** **Sample ID:**	 2014-09-26 RW-090314-NB	NUTRIENT ANALYSIS

		Analysis (as rec'd)	Analysis (dry weight)	Total content, lbs per ton (as rec'd)
NUTRIENTS				
Nitrogen				
Total Nitrogen	%	1.36	4.14	27.2
Organic Nitrogen	%	1.10	3.36	22.0
Ammonium Nitrogen	%	0.258	0.786	5.2
Nitrate Nitrogen	%	< 0.01	----	----
Major and Secondary Nutrients				
Phosphorus	%	0.44	1.34	8.8
Phosphorus as P2O5	%	1.01	3.08	20.2
Potassium	%	0.90	2.74	18.0
Potassium as K2O	%	1.08	3.29	21.6
Sulfur	%	0.20	0.61	4.0
Calcium	%	0.78	2.38	15.6
Magnesium	%	0.41	1.25	8.2
Sodium	%	0.160	0.488	3.2
Micronutrients				
Zinc	ppm	77.1	235	0.2
Iron	ppm	3520	10725	7.0
Manganese	ppm	131	399	0.3
Copper	ppm	< 20	----	----
Boron	ppm	< 20	----	----
OTHER PROPERTIES				
Moisture	%	67.18		
Total Solids	%	32.82		656.4
Organic Matter	%	19.40	59.11	388.0
Ash	%	13.40	40.83	268.0
C:N Ratio		8 : 1		
Total Carbon	%	10.41	31.72	
Chloride	%	0.33	1.01	
pH		8.2		

REFERENCES

Aillery, M., N. Gollehon, R. Johansson, N. Key, & Ribaudo, M. (2005). Managing manure to improve air and water quality. Economic Research Report No. 9, United States Department of Agriculture. Washington, DC. Retrieved from www.ers.usda.gov/publications/ERR9/.

ANSI/ASAE Standards. (R2012). S319.4: Method of determining and expressing fineness of feed materials by sieving. St. Joseph, Mich.: ASABE.

APHA, AWWA, & WEF Standards. (2012). Standard methods for the examination of water and wastewater. 22nd Edition. Editors: E.W. Rice, R.B. Baird, A.D. Eaton, and L.S. Clesceri. Washington, DC.

ASABE Standards. (2005). D384. 2: Manure production and characteristics. St. Joseph, Mich.: ASABE.

ASTM Standards. (2007). D7367 – 07: Standard test method for determining water holding capacity of fiber mulches for hydraulic planting. ASTM International. West Conshohocken, PA. Retrieved from www.astm.org

Barberg, A., Endres, M., Salfer, J., & Reneau, J. (2007a). Performance and welfare of dairy cows in an alternative housing system in Minnesota. *J. Dairy Sci.* 90(3), 1575-1583. Retrieved from http://dx.doi.org/10.3168/jds.S0022-0302(07)71643-0.

Barberg, A., Endres, M., & Janni, K. (2007b). Compost dairy barns in Minnesota: A descriptive study. *Appl. Eng. Agric*. Vol. 23(2): 231-238.

Bewley, J., & Taraba, J. (2009). Compost bedded pack barns in Kentucky. Cooperative Extension Service. University of Kentucky. College of Agriculture Extension Factsheet ID-178. Lexington, KY.

Bewely, J., Taraba, J. and Day,G. (2012). Compost bedded pack barn design: Features and management considerations. Cooperative Extension Service. University of Kentucky College of Agriculture Extension Factsheet. ID-206. Lexington, KY. Retrieved from http://www2.ca.uky.edu/agc/pubs/id/id206/id206.pdf

Bewley, J. M., Taraba, J. L., McFarland, D., Garrett, P., Graves, R., Holmes, B., Kammel, D., Porter, J., Tyson, J., Weeks, S., and Wright, P.. (2013). Guidelines for managing compost bedded-pack barns. *The Dairy Practices Council*. Retrieved from https://www.dairypc.org/catalog/guidelines-for-managing-compostbedded-pack-barns.

Bond, B. J., Burns, R. T., Henry, C. G., Trooien, T. P., Pohl, S. H., Moody, L. B., Helmers, M. J., and Lawrence, J. D. (2011). Comparison of construction costs for vegetative treatment systems in the Midwestern United States. *Appl. Eng. in Agric.,* 27(3):413-423.

Changirath, S., Halbach, T. R., & Dorff, R. (2011). Media and media mix evaluation for dairy barn compost bedding systems. Project No. 00013063. Final Report. St. Paul, MN. Department of Soil, Water and Climate, University of Minnesota.

Copeland, C. (2006). Animal waste and water quality: EPA regulation of Concentrated Animal Feeding Operations (CAFOs). Washington, D.C.: Congressional Research Service, Library of Congress.

Doran, B., Euken, R., & Spiehs, M. (2010). Hoops and mono-slopes: What we have learned about management and performance. Feedlot Forum 2010. Ames, IA. Iowa Beef Center at Iowa State University.

Drissler, M., Gaworski, M., Tucker, C., & Weary, D. (2005). Freestall maintenance: Effects on lying behavior of dairy cattle. *J. Dairy Sci*. 88(7), 2381-2387.

Eghball, B., & Power, J. F. (1998). Management of manure from beef cattle in feedlots and from minor classes of livestock. Conservation Research Report 44. Agricultural Uses of Municipal, Animal, and Industrial Byproducts. U.S. Department of Agriculture, Agricultural Research. Retrieved from www.ars.usda.gov/is/np/agbyproducts/agbycontents.htm.

Endres, M. I., & Janni, K. A. (2008). Compost bedded pack barns for dairy cows. *Lincoln, NE. Online Extension. Univ. of Nebraska-Lincoln.* Retrieved from http://www2.ca.uky.edu/agc/pubs/id/id206/id206.pdf.

Endres, M., & Barberg, A. (2007). Behavior of dairy cows in an alternative bedded-pack housing system. *J. Dairy Sci.* 90(9), 4192-4200.

Euken, R. (2010). A survey of manure characteristics from bedded confinement buildings for feedlot beef production. Ames, IA. Final report. Iowa State University Animal Industry Report, A.S. Leaflet R2526. Iowa State Univ. Dept. of Anim. Sci.

Euken, R., Doran, B., Clark, C., Shouse, S., Ellis, S., Loy, D., & Schulz, L. (2015). Beef feedlot systems manual. No. PM1867. Ames, IA. City state Iowa State University.

Fregonesi, J., Tucker, C., & Weary, D. (2007). Overstocking reduces lying time in dairy cows. *J. Dairy Sci.* 90(7), 3349-3354.

Fregonesi, J., Veira, D., Von Keyserlingk, M., & Weary, D. (2007). Effects of bedding quality on lying behavior of dairy cows. *J. Dairy Sci.* 90(12), 5468-5472.

Gay, S. W. (2009). Bedded-pack dairy barns. Virginia Tech Cooperative Extension. 442-124.
Retrieved from http://pubs.ext.vt.edu/442/442-124/442-124.html

Goldsmith, P. D., & Idris, H. (2001). The economic impact of illinois' livestock industry. Report #94. College of ACES, University of Illinois at Urbana-Champaign.

Herbert, S., Hashemi, M., Chickering-Sears, C., & Weis, S. (2005). Bedding options for livestock and equine. Publication 08-5, University of Massachusetts Extension. Retrieved from http://Extension.umass.edu/cdle/factsheets/bedding-options-livestock-and-equine.

Hill, J. (2000a). Bedding management for large pen deep bed swine finishing facilities. Swine Housing. Des Moines, IA. USA, 9-11, October, 2000. 310-316. ASABE.

Hill, J. (2000b). Deep bed swine finishing. *5º Seminário Internacional de Suinocultura*. Expo Center Norte, Sao Paulo, Brasil. 83-88 p.

Honeyman, M. S., Harmon, J. D., Shouse, S. C., Busby, W. D., & Maxwell, D. L. (2008). Feasibility of bedded hoop barns for market beef cattle in Iowa: Cattle performance, bedding use, and environment. *Appl. Eng. Agric.,* 24(2), 251.

James, R., Eastridge, M.L., Brown, L.C., Elder, K.H., Foster, S.S., Hoorman, J.J., Joyce, M.J., Keener, H.M., Mancl, K., Monnin, M.J., Rausch, J.N., Smith, J.M., Tuovinen, O., Watson, M.E., Wicks, M.H., Widman, N., and Zhao, L. (2006). Ohio livestock manure management guide. Bulletin 604. The Ohio State University Extension.

Janni, K. A., Endres, M. I., Reneau, J. K., & Schoper, W. (2006). Compost barns: An alternative dairy housing system in Minnesota. Paper (Vol. 64031).

Janni, K. A., Endres, M. I., Reneau, J. K., & Schoper, W. W. (2007). Compost dairy barn layout and management recommendations, *Appl. Eng. Agric.* vol., 23(1): 97-102.

Kains, F., Lovell, B., Payne, M. & Tremblay, R. (2014). Livestock bedding alternatives. Fact Sheet 97-029. Ontario, CA. Ministry of Agriculture Food and Rural Affairs. Retrieved from http://www.omafra.gov.on.ca/english/environment/facts/97-029.htm.

Kammel, D.W. (2004). Hoop barns for dairy cattle. MWPS. AED-51. Ames, IA. MidWest Plan Service.

Kuan, Y., & Liong, M. (2008). Chemical and physicochemical characterization of agrowaste fibrous materials and residues. *J. Agric. Food Chem.*, 56(19), 9252-9257.

Larney, F. J., Buckley, K. E., Hao, X., & McCaughey, W. P. (2006). Fresh, stockpiled, and composted beef cattle feedlot manure. *J. Environ. Qual.*, 35(5), 1844-1854.

LMFA. (1996). 510 ILCS 77/ (effective 5-21-1996). Livestock Management Facilities Act. Illinois Compiled Statutes. Retrieved from: http://www.ilga.gov/legislation/ilcs/ilcs3.asp?ActID=1720&ChapAct=510%A0ILCS%A077/&ChapterID=41&ChapterName=ANIMALS&ActName=Livestock+Management+Facilities+Act%2E.

McFarland, D., Garrett, P., Graves, R., Holmes, B., Kammel, D., Porter, J., & Wright, P. (2013). Guidelines for managing compost bedded-pack barns. Milford, PA. The Dairy Practices Council. Retrieved from https://www.dairypc.org/catalog/guidelines-for-managing-compostbedded-pack-barns.

Midwest Plan Service, MWPS-18. (2000). Handbook: Livestock Waste Facilities, 2nd Ed. Ames, Iowa: Iowa State University.

National Dairy Environmental Stewardship Council. (2005). Cost-effective and environmentally beneficial dairy manure management practices. San Francisco, CA. Sustainable Conservation. Retrieved from http://www.suscon.org/dairies/pdfs/NDESCreportCostEffective.pdf.

Patriquin D. (2004) Water, soil and organic matter: a complex relationship. *The Canadian Organic Grower*. Retrieved from http://www.cog.ca/documents/Water.pdf.

Pepple, L. M., & Gates, R. S. (2013). Evaluation of available design criteria for modern deep-bed pack beef production facilities. *19-22 October, Rongchang, Chongqing, China. pp 282-288.*

R Core Team. (2012). R: A language and environment for statistical computing. R foundation for statistical computing, Vienna, Austria. ISBN 3-900051-07-0. Retrieved from http://Www.R-project.org/.

Shouse, S., Honeymanm, M., and Harmon, J. (2004). Hoop barns for beef cattle. AED 50. Ames, IA. Midwest Plan Service, Iowa State University.

South Dakota NRCS. (2011). Beef and dairy bedded pack barn planning and design. Design Technical note. No. SD2011-1. USDA Natural Resource Conservation Service. Retrieved from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs141p2_036372.pdf.

Spiehs, M., Brown Brandl, T., Jaderborg, J., Dicostanzo, A., Purswell, J., & Davis, J. (2013). Water holding capacity and evaporative loss from organic bedding materials used in livestock facilities. ASABE Paper No. 131595738. St. Joseph, Mich.: ASABE.

Spiehs, M. J., Woodbury, B. L., Doran, B. E., Eigenberg, R. A., Kohl, K. D., Varel, V. H., ... & Wells, J. E. (2011). Environmental conditions in beef deep-bedded mono-slope facilities: A descriptive study. *Trans. ASABE.,* 54(2), 663-673.

Tucker, C., & Weary, D. (2004). Bedding on geotextile mattresses: How much is needed to improve cow comfort? *J. Dairy Sci.*, 87(9), 2889-2895.

USDA-NASS. (2012). Census of Agriculture. USDA National Agriculture. Retrieved from http://www.agcensus.usda.gov/Publications/2012/Full_Report/Census_by_State/Illinois/

Van Horn, H.H., and M.B. Hall. (1997). Agricultural and environmental issues in the management of cattle manure. Agricultural uses of by-products and wastes. *American Chemical Society Symposium* Series 668:91-109. Washington, DC.

Van Horn, H., Wilkie, A., Powers, W., & Nordstedt, R. (1994). Components of dairy manure management systems. *J. Dairy Sci.*, 77(7), 2008-2030.

Vanderholm, D. H. (1979). Handling of manure from different livestock and management systems. *J. Anim. Sci.*, 48(1), 113-120.

Westendorf, M. L. and Krogmann, U. (2006). Horse Manure Management: Bedding Use. Fact Sheet #537. Rutgers Cooperative Extension. New Jersey Agricultural Experiment Station. Rutgers University. Retrieved from http://www.esc.rutgers.edu/publications/stablemgt/fs537.htm.

Wheeler, E., Koenig, B., Harmon, J., Murphy, P., and Freeman, D. (2005). Horse facilities handbook. Ames, IA. Midwest Plan Service. Iowa State University.