Particle Density, Particle Size, and Nutrient Distribution of Flushed Dairy Manure

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Authorization to Submit Thesis

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Abstract

The handling of large volumes of liquid manure produced by hydraulic flushing systems can be challenging for dairy farmers. The high solid content in flushed dairy manure causes numerous challenges during manure handling, and the high nutrient content limits the amount of manure that can be applied onto cropland. The knowledge of particle density, particle size, and nutrient distribution of flushed dairy manure would allow dairy farmers to select appropriate manure treatment technologies and make better manure nutrient management on their farms.

The major goal of this study was to understand the particle density, particle size, and total nitrogen (TN) and total phosphorous (TP) distributions of flushed dairy manure by using four commercial dairies in Southern Idaho as case studies. The study also aimed to examine the statistical significance of using different pore-sized inclined screen separators for solids and nutrients removal from flushed dairy manures of the four dairies.

The particle densities of flushed dairy manure solids were determined by the pycnometer method using a methanol medium. A new technique—wet sieving combined with the hydrometer-pipette method—was used to determine the particle size and nutrient distributions of the flushed dairy manures. Nutrient analyses were carried out using the Hach methods: TNT 880 for TN and TNT 845 for TP.

The flushed dairy manures of the four dairies differed in the initial total solid as well as nutrient contents with total solids (TS) ranging from 2.23% to 7.69%, TN ranging from 0.08% to 0.19%, and TP ranging from 0.04% to 0.13%. The particle densities of flushed dairy manure solids were found to vary with particle size, and the average particle densities of dried

solids in flushed manures of dairies, #1, #2, #3, and #4 were found to be 1.48, 1.39, 1.37, and 1.30 g/cm^3, respectively, much lower than the commonly used particle density of soils of 2.65 g/cm^3. The distributions of solids and nutrients in flushed dairy manures also varied between the four dairies and were found to be site-specific. However, regardless of the dairy, the majority of TS, TN, and TP in flushed manures were observed at diameters smaller than 0.5 mm. Dairies, #1, #2, #3, and #4 had 63.85%, 58.17%, 57.94%, and 51.50% of TS smaller than 0.5 mm in diameter. Similarly, the percentages of TN and TP observed at diameters smaller than 0.5 mm for dairies, #1, #2, #3, and #4 were 72.00%, 75.14%, 75.76%, and 61.92% and 85.64%, 70.58%, 69.28%, and 61.35%, respectively. The statistical differences between the solid and nutrient removal capacities of different pore-sized inclined screen separators were found to be dairy-specific.

From this study, it was estimated that 0.5-mm pore-sized inclined screen separators would remove between 25.41% and 37.40% of TS, 24.24% and 38.08% of TN, and 14.36% and 38.65% of TP from flushed dairy manures with initial TS ranging from 2.23% to 7.69%. This suggests that the inclined screen separators with pore size larger than 0.5 mm would remove only a fraction of total solids, total nitrogen, and total phosphorus from flushed dairy manures, and most of the TS, TN, and TP would remain in the liquid fraction after solid-liquid separation. Therefore, commercial dairies that rely on inclined screen separators with pore sizes larger than 0.5 mm for solid-liquid separation might need to look beyond the 0.5-mm pore-sized screen separators to remove higher quantities of solids and nutrients from their flushed dairy manures.

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Chapter 1: Introduction

The global dairy industry is gradually shifting from small and medium-sized dairy farms to much larger farms. The transformation is more pronounced in the United States (U.S.). Today, the number of dairy farms in the U.S. is one-fourth of what it was 30 years ago, and the decline in the number of dairy farms has been rapid lately as the number of licensed dairy farms slumped by 15% between 2017 and 2019 (MacDonald et al., 2020). Although the number of dairy farms has declined, the total milk production has increased over the years. The U.S. produces about 50% more milk than it did 30 years ago (MacDonald et al., 2020). This is due to the transformation of smaller dairy farms to large-sized farms that house a high number of cows in a confined space. These concentrated livestock production units generate large volumes of manure that contain appreciable amounts of solids and nutrients having the potential to contaminate soil, water, and air via leaching, surface run-off, and emissions of odors and greenhouse gases (Petersen et al., 2007).

Idaho is among the top five milk-producing states in the United States with, as of 2019, around 437 dairy farms. And almost all dairies in Idaho are family-owned, and mostly concentrated in the Magic Valley Region of Southern Idaho where the average number of cows per dairy is 1,586 (IDA, 2019). The Magic Valley region is the heart of Idaho’s dairy production, accommodating about 70% of the state’s dairy cows (Salant et al., 2017). Some large commercial dairies in the Magic Valley region use hydraulic flushing systems that generate large volumes of liquid manure requiring serious handling and management efforts (Chen et al., 2014). Such large volumes of flushed manure present several challenges to dairy farmers for the proper management of dairy manure, especially if there is a limited nearby land area for application. Technologies that improve manure management and separate solid particles from the liquid fraction of dairy manure are attractive to Idaho dairy farms for easier and cheaper manure handling (Meyer et al., 2004). Identifying potential manure management technologies to efficiently reduce the solids and nutrients present in flushed dairy manure is vital for the sustainability of Idaho's dairy industry (Kruger et al., 2019).

Livestock farms can handle and manage manure either in solid or liquid form. Large commercial dairies prefer liquid manure handling systems for manure management because of the ease of mechanization and low labor requirement (Hegg et al., 1981; Zhang & Westerman, 1997). The liquid form of manure is also comparatively easier to handle, store, and land-apply (Mukhtar et al., 2018; Christensen & Sommer, 2013) as the liquid manure can be easily pumped and applied to farmland by mixing with irrigation water using either big guns or center pivot irrigation systems with small nozzles (Lorimor et al., 2004). Hydraulic flushing is becoming one of the preferred options among modern dairies to remove manure from alleyways (Bhavya, et al., 2018) because of the low labor requirement, lower operating costs, and increased sanitation inside the barn (Harner & Murphy, 1997). In a hydraulic flush system, the manure on the barn floor is removed via a large volume of water flowing from one end of the barn to the other (James et al., 2006; Janni & Cortus, 2020). Fresh water could be used for flushing, but recycled lagoon water is more common among modern dairy farms (Janni & Cortus, 2020).

The handling and management of the massive volumes of liquid manure produced from the flushing systems can be a challenge for most dairy farmers. The high solid contents in liquid manure eventually settle down to the bottom of the lagoons leading to the reduction in the storage volume of lagoons, thus requiring more frequent lagoon dredging (Wright, 2005).

The frequent dredging and cleaning of lagoons is costly and adds a financial burden on farmers. Large-sized solids in liquid manure can clog or even damage pumps, transfer pipes, and sprinkler nozzles, and higher energy is required for pumping the manure with higher solids content via pipes (Ford & Fleming, 2002). Mukhtar et al. (2018) and Wright (2005) argued that a high solid content in liquid manure also leads to an increased emission of odors, ammonia, and other reactive organic gases due to increased organic loading in lagoons, reduced lagoon effluent quality which can lead to clogging of spray and drip irrigation pipes, loss of manure solids, and the contamination of surface or ground water if a lagoon system should fail. Further, liquid manure with high solids can form crusts and seal soil surfaces during land application which can impact soil properties like aeration, infiltration, and evaporation (Assouline, 2004; Touma et al., 2011). The high nutrient contents in liquid manure can also be a problem. The excess land application of nutrient-rich liquid manure could result in nutrient overloading, and manure nutrients could eventually end up in the water bodies via leaching and runoff. Stringent environmental regulations regarding the land application of manure and onsite nutrient management limit the amount of liquid manure that can be applied on agricultural fields (Chen et al., 2014; Leytem et al., 2013). Transporting the excess liquid manure to distant places could be an option but is expensive. Therefore, proper handling and management of flushed dairy manure are vital for the profitability of dairy farms.

After collection of liquid manure following flushing, several options are available to dairy farmers for manure treatment and management: i) solid-liquid separation ii) chemical precipitation, coagulation, and flocculation iii) evaporation iv) membrane separation, etc. (Hjorth et al., 2011). Among these methods, solid-liquid separation is increasingly becoming popular among dairy farmers for easy handling and management of liquid dairy manure (Peters et al., 2011).

The solid and liquid fractions of flushed dairy manure can be segregated by mechanical separators with screens (stationary, vibrating, or rotating cylindrical), belt pressers (belt, screw, or perforated roll), centrifuges, or sedimentation/settling basins (Chastain et al., 2001; Fulhage & Pfost, 1993; Ford & Fleming, 2002; Meyer et al., 2004; Wright, 2005; Wu & Zhong, 2020). Effective solid-liquid separation can remove a considerable quantity of organic matter and nutrients from liquid manure and prevent excess nutrients from being transferred to the agricultural soils during land application (Lorimor et al., 2006). The separated solid fraction can be used as soil amendments, a substrate for composting, bedding material in dairy barns, feed for generating biogas (methane), or sold to plant nurseries and other markets (Ford & Fleming, 2002; Fulhage & Pfost, 1993; Mukhtar et al., 2018). The liquid fraction can be recycled as flush water or stored in lagoons or manure ponds, which can then be applied on agricultural lands during cropping seasons as fertilizer or irrigation water (Ford & Fleming, 2002). The removal of manure solids allows dairy farms to increase the herd size without expanding the lagoon size (Fulhage & Pfost, 1993). According to Rico et al. (2012), screens are the most extensively used mechanical separators by dairy farmers. Still today, most dairies use screen separators for solid-liquid separation as they are comparatively cost-effective and energy-efficient (Ford & Fleming, 2002; Møller et al., 2000).

The proper selection of solid-liquid separation equipment is an important decision for dairy farmers due to the negative consequences that can ensue if the manures are not managed properly. Inefficient solid-liquid separation leads to a higher amount of solids and nutrients passing onto the liquid portion of manure. As described previously, the high solid and nutrient contents in the liquid fraction of manure would increase the overall manure handling costs. To avert such problems, the solid-liquid separation technologies need to be wisely selected based on the particle density, particle size, and nutrient distribution of the flushed dairy manure.

However, particle size and nutrient distributions of manures are often overlooked when it comes to optimizing the design and operation of animal manure management systems, and research on municipal wastewater indicates that particle sizes have a direct influence on nutrient concentration and play a major role in the treatment and system performance (Wright, 2005). The knowledge of particle density, particle size, and nutrient distribution of flushed dairy manure is critical for dairy farmers to make informed decisions on what type of manure and nutrient management technologies they wish to implement on their dairy operations. Ford & Fleming (2002) pointed out that the analysis of particle size distribution of manure would be the greatest single improvement to the mechanical separator test protocols. The knowledge of particle density of manure solids is important for designing and operating manure handling and processing systems (Wilkie, 2005) including for the construction of manure storage and settling ponds/lagoons. This would help to reduce the premature filling of manure lagoons and the costs associated with frequent dredging and cleaning of lagoons. The information on the physical properties of manure including particle density and particle size is indispensable for designing pumps, solid-liquid separation equipment, and storage tanks and estimating the energy required for pumping and handling of manure (Christensen & Sommer, 2013). Thorough knowledge of particle density, particle size, and nutrient distribution would reduce the overall manure handling costs of dairy operations.

Although there have been some research efforts to quantify the particle size and nutrient distribution of fresh dairy manure in the past (Landry et al., 2004; Meyer et al., 2007; Møller et al., 2002; Peters et al., 2011; Wright, 2005; Wu & Zhong, 2020), little attention has been given toward the distribution of solids and nutrients in flushed dairy manure. The compositions of fresh dairy manure and flushed dairy manure are different. The flushed dairy manure contains additional solids sourced from spilled feedstuffs, bedding materials, animal hairs, and recycled lagoon flush water. Therefore, the use of the information on particle size distribution (PSD) of raw dairy manure might not be reliable for approximating the PSD of flushed dairy manure.

The general objective of this study was to investigate the particle density of flushed dairy manure solids and investigate the particle size, total nitrogen (TN), and total phosphorous (TP) distributions of flushed dairy manure by taking the case studies of four commercial dairies located in Southern Idaho, USA. The overarching goal was to relay the information obtained from this study to those dairymen wanting to make informed decisions on the implementation of appropriate manure treatment technologies and nutrient management plans on their dairy farms.

The specific objectives of the study were to:

1. Identify the initial total solid and nutrient contents in the flushed manures of the four dairies.
2. Identify the particle density of solids present in the flushed dairy manures of the four dairies.
3. Determine the particle size distribution of solids in the flushed dairy manures of the four dairies.
4. Identify the distribution of total nitrogen and total phosphorus in the flushed dairy manures of the four dairies.

5. Examine the statistical significance of using different pore-sized inclined screen separators for solids and nutrients removal from the flushed dairy manures of the four dairies.

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Chapter 2: Review of the Literature

This chapter summarizes the literature relevant to this study, identifies the gaps in the literature, and states how this study will help to fill some of those gaps. The chapter begins by discussing the composition of flushed dairy manure and the current liquid dairy manure handling systems and management practices. This is followed by the discussion of problems related to liquid dairy manure handling. It then revisits the past studies on particle density, particle size, and nutrient distribution of flushed dairy manure for understanding what has been done so far to address the issues. The literature gap is then identified which bolsters the case for this study.

2.1 Composition of flushed dairy manure

The flushed dairy manure from animal housings comprises a mixture of feces, urine, wasted feedstuffs, bedding materials (including chopped straw and hay, wood shavings, sawdust, sphagnum, sand, and ground corn cobs), spilled drinking water, flush water, and wash water (Christensen & Sommer, 2013; Ford & Fleming, 2002; Hjorth et al., 2011). Houlbrooke et al. (2011) had categorized dairy manure into three forms: solid manure (>15% dry matter), slurry (5–15% dry matter), and liquid effluent (<5% dry matter). Researchers have reported a wide range of dry matter content in flushed dairy manure: 0.38–7.7% dry matter reported by Chastain et al. (2001), Christensen & Sommer (2013), Ford & Fleming (2002), Hegg et al. (1981), and Meyer et al. (2004). Several researchers (Chastain et al., 2001; Meyer et al., 2007; Zhang & Westerman, 1997) have argued that the compositions and characteristics of flushed dairy manure are affected by biological, cultural/management, and environmental factors.

Livestock species, growth stage, digestive and assimilative power of cows, feeding practices, manure collection and storage systems, amount of water added to the manure, the quantity of wasted feed, washwater, spilled drinking water, and bedding material mixed with manure, manure collection methods, climatic conditions (wet or dry), etc. are some of the factors affecting manure composition (Hjorth et al., 2011; James et al., 2006; Jensen & Sommer, 2013; Zhang & Westerman, 1997; Zhang, 2002).

Dairy manure also contains an appreciable quantity of plant nutrients (Hjorth et al., 2011; Schröder et al., 2014) including nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), copper (Cu), zinc (Zn), chlorine (Cl), boron (B), iron (Fe), and molybdenum (Mb) (Chastain & Camberato, 2004). The precise quantification of nutrients in dairy manure is difficult as the concentrations of nutrients vary with animal health and dairy management practices. According to Christensen & Sommer (2013), dairy farmyard manure (FYM) consists of about 133, 23, and 202 g of N, P, and K per kg (dry matter) of manure, while liquid dairy manure (slurry) contains 42, 11, and 59 g of N, P, and K per kg (dry matter) of manure. The nutrient content of flushed dairy manure is much different than raw dairy manure. Researchers have reported a varying concentration of nutrients in flushed dairy manures. Chastain et al. (2001), Christensen & Sommer (2013), and Ford & Fleming (2002) reported about 0.14%, 0.32%, and 0.29% (wet wt. basis) of total nitrogen (TN) and 0.09%, 0.085%, and 0.08% (wet wt. basis) of total phosphorous (TP) in flushed dairy manures.

2.2 Current dairy manure handling and management practices of liquid dairy manure

The prudent handling of manure and avoiding the over-application of manure into the agricultural lands are crucial for minimizing the negative environmental implications of dairy manure and maintaining the sustainability of the dairy industry. Proper treatment and management of farm manure can reduce various pollution risks, minimize offensive odors, draw some value from both solid and liquid fractions of manure, and make overall farm operation more efficient (Burton, 2007).

The freestall barn is the most common dairy housing system in the U.S., where cows are free to lie down and move around to eat and drink (Chastain, 2019). In modern tiestall and freestall dairy housing systems, as the cows are constantly moving, dairy manure is usually composed of animal excreta (feces and urine), spilled feed, animal hairs, and bedding materials with high total solids (TS) content making it harder to handle the manure in solid form. Therefore, large commercial dairies prefer liquid manure handling systems for manure management because of the ease of mechanization and low labor requirement (Hegg et al., 1981; Zhang & Westerman, 1997). It is also comparatively easier to handle, store, and land-apply liquid manure (Mukhtar et al., 2018; Christensen & Sommer, 2013) as the liquid manure can be easily pumped and applied to farmland by mixing with irrigation water using either big guns or center pivot irrigation systems with small nozzles (Lorimor et al., 2004).

Mechanical scraping and hydraulic flushing systems are two methods of barn floor cleaning that are common among modern commercial dairies that use freestall barns for animal housing (Bhavya et al., 2018; Chastain, 2019; Gushansky et al., 2017; Janni & Cortus, 2020). In mechanical scraping, tractor-mounted or automatic scrapers are used to scrape manure out of the barn, and water is later mixed with manure for dilution and conversion into liquid manure, while in the hydraulic flush system, the manure on the alleyways is removed via a large volume of water flowing from one end of the barn to the other (Gushansky, et al., 2017; James et al., 2006; Janni & Cortus, 2020). Fresh water could be used for flushing, but recycled lagoon water is more common among modern dairy farms (Janni & Cortus, 2020). The hydraulic flushing system is becoming one of the popular systems among modern dairies to remove manure off the barn (Bhavya et al., 2018) because of the low labor requirement, lower operating costs, and increased sanitation inside the barn (Harner & Murphy, 1997). Also, scrapers have been shown to have more environmental emissions as a thin film of manure may be left on the ground after scraping, which may create in-barn volatile organic compounds emissions, while a flush system removes almost all manure from the ground (Gushansky, et al., 2017).

The flush system (and the scraping system after dilution) produces a massive volume of liquid manure in confined animal feeding operations (CAFOs) as 240–620 gallons of flush water per cow per day are required for flushing (Harner & Murphy, 1997). The handling and treatment of such huge volumes of flushed dairy manure can be a challenge for dairy farmers, especially, if there is limited nearby farmland for application. After collection of slurry following flush or scrape, dairy farmers have several options available to them for manure treatment and management including solid-liquid separation, chemical precipitation, coagulation, and flocculation, evaporation, membrane separation, and biological treatment (Bernet & Béline, 2009; Hjorth et al., 2011).

Manure management strategies vary with dairy farm type. In the U.S., the primary manure management strategies for open lot farms are solids removal via settling basins followed by land application of the liquids or total containment/detention basins (lagoons) before land application. Likewise, confined dairy farms store liquid manure in slurry basins or pits, digestion in digesters, storage in aerobic and anaerobic lagoons, and solid-liquid separation using mechanical separators followed by storage of liquid fraction in pits/lagoons (Lorimor et al., 2006). Daily scraping, hauling, and spreading of manure on agricultural lands also exist in some small dairy farms with both indoor and outdoor lots (Lorimor et al., 2006). Less emphasis has been given toward the wetland treatment systems and chemical precipitation methods for the management of animal manure. Although covered lagoons and anaerobic digesters can reduce odors and prevent the release of unwanted gases into the atmosphere, they lack incentives for widespread adoption by livestock farms because of high capital costs and high management requirements (Lorimor et al., 2006). Further, even after anaerobic digestion, the digestate maintains all manure nutrients that need to be managed properly (Pandey & Chen, 2021).

Solid-liquid separation is increasingly becoming popular among dairy farmers for easy handling and management of liquid dairy manure (Peters et al., 2011) as they are often relatively cheap, easy to operate, and require little attention (Burton, 2007).

2.3 Solid-liquid separation of liquid dairy manure

Solid-liquid separation is a widely adopted and probably, the most popular manure treatment practice among dairy farmers (Gooch et al., 2005; Wu & Zhong, 2020). The effective solid-liquid separation can remove an appreciable quantity of organic matter and nutrients from liquid manure and minimize the nutrient load on soils during the land application of liquid manure (Lorimor et al., 2006). After solid-liquid separation, the solid fraction could be used as soil amendments, a substrate for composting, bedding material in dairy barns, or feed for generating biogas (methane) (Mukhtar et al., 2018; Ford & Fleming, 2002). The liquid fraction could be recycled as flush water or stored in lagoons or manure ponds, which could then be applied on agricultural lands during cropping seasons (Ford & Fleming, 2002).

There are several technologies available for segregating solid and liquid fractions of manure including mechanical separators with screens (stationary, vibrating, rotating cylindrical, or conveyer belt), belt pressers (belt, screw, filter, or perforated roll), centrifuges or hydrocyclones, sedimentation/settling basins, or chemical precipitation (Burton, 2007; Chastain et al., 2001; Fulhage & Pfost, 1993; Ford & Fleming, 2002; Meyer et al., 2004; Wright, 2005; Wu & Zhong, 2020). Screen separators are the most popular and extensively used solid-liquid separation technology by U.S. dairy farmers (Rico et al., 2012). Still today, most dairies use screen separators for solid-liquid separation as they are comparatively cost-effective and energy-efficient than other solid-liquid separation technologies (Ford & Fleming, 2002; Møller et al., 2000).

However, several problems could arise if the solid-liquid separation is inefficient. Ineffective solid-liquid separation could lead to more solids being retained in liquid fractions and transferred to the lagoons. This would result in a lower amount of solids available for composting, bedding, or other beneficial purposes (Gooch et al., 2005). Excess levels of particulate matter in liquid fractions of manure could cause several problems during manure handling (Wright, 2005). Large-sized solids in liquid manure can clog or even damage pumps and transfer pipes, and it requires higher energy for pumping the manure with higher solids content via pipes (Ford & Fleming, 2002; Mukhtar et al., 2018; Wright, 2005). Similarly, manure solids can settle down and accumulate at the bottom of lagoons over time leading to the reduction in the lagoon capacity (Wright, 2005). This requires frequent dredging and cleaning of lagoons which will add a financial burden on dairy farmers. Ford & Fleming (2002) and Wright (2005) argued that high solids in liquid manure could also lead to an increased emission of odors, ammonia, and other reactive organic gases due to increased organic loading in lagoons, reduced lagoon effluent quality which can lead to clogging of spray and drip irrigation pipes, loss of manure solids, and the potential contamination of surface or ground water if a lagoon system should fail. Further, liquid manure with high solids can form crusts and seal soil surfaces during land application which can impact soil properties like aeration, infiltration, and evaporation (Assouline, 2004; Touma et al., 2011).

Likewise, in the case of inefficient solid-liquid separation, most nutrients would be retained in the liquid portion of flushed dairy manure, and the land application of such nutrient-rich liquid fraction could cause nutrient overloading (Pandey & Chen, 2021). High nutrients in liquid manure (especially nitrogen and phosphorous) limit the amount of manure that can be applied on agricultural lands. With limited agricultural lands, excess liquid manure needs to be transported to distant places which is an expensive task. If over-applied, nutrients in liquid manure could eventually end up in water bodies by leaching or runoff, thereby posing a threat to water quality (Burton & Turner, 2003; Ford & Fleming, 2002). It is, therefore, important to properly separate solids (along with nutrients) from liquid manure for better manure handling and minimizing environmental pollution.

Proper selection of solid-liquid separation equipment is an important decision for dairy farmers due to the negative economic as well as environmental consequences that can ensue if the manures are improperly managed. To avert such problems, the solid-liquid separation technologies need to be optimized, for which further information is required on the particle density, particle size, and nutrient distribution of flushed dairy manure.

2.4 Particle density of flushed dairy manure

The particle density of a solid is the ratio of mass to the volume of the solid (Bohnhoff & Converse, 1987; Weindorf & Wittie, 2003), generally expressed in grams per cubic centimeter (g/cm^3) or kilograms per cubic meter (Kg/m^3) (Hillel, 1998). It represents how heavy a solid is and gives an idea about the differential rate of settling of solids. The particle density affects the rate of settlement of solids in technologies that separate solids and nutrients (Christensen & Sommer, 2013). In manure lagoons, solids settle down based on their particle densities, solids with higher densities settle faster, while lighter solids settle slower (Christensen et al., 2013).

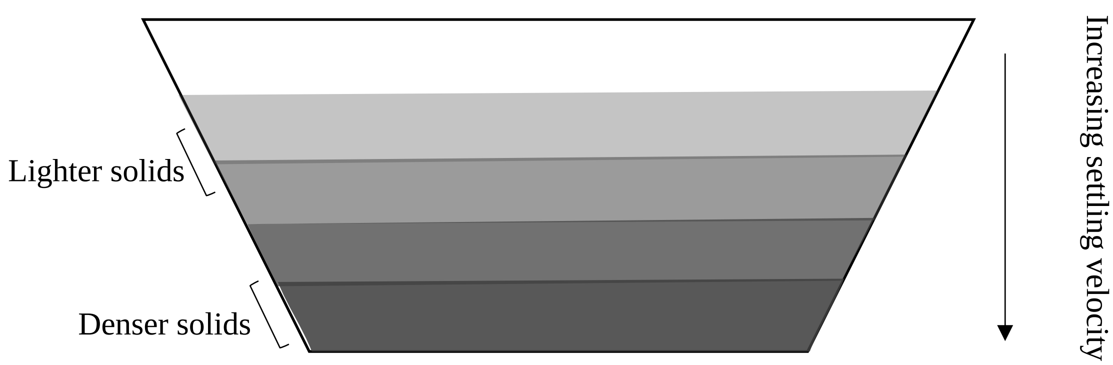

Figure 2.1: Diagrammatic representation of a typical manure lagoon.

The knowledge of particle density of manure solids is important for designing and operating manure handling and processing systems (Wilkie, 2005). The information is also important for researchers and engineers to determine the storage volume of lagoons or storage tanks and energy requirement for pumping and handling of manure (Christensen & Sommer, 2013; Wilkie, 2005). However, little emphasis has been given toward investigating the particle density of solids of flushed dairy manure. A few studies investigating the particle density of manure that could be found in the literature (mostly made before the 2000s) have been found to be made on fresh manure only.

2.4.1 Method for determining the particle density of flushed dairy manure

No studies have been made on the particle density of flushed dairy manure, and the literature on the particle density of dairy manure only concerns fresh/raw manure. For determining the particle density of raw dairy manure, the past researchers adopted the same standard procedure used for determining the particle density of soils i. e. the pycnometer method developed by the American Society for Testing and Materials (ASTM, 2014). However, instead of de-ionized (DI) water, those studies used less dense liquids as some manure solids are lighter than water, and as a result would not settle out of suspension thereby compromising the accurate measurement of displaced volume (Weindorf & Wittie, 2003). According to Lam et al. (2007) and Day & Panda (1966), dry wheat straw and dry chopped hay particles have lower particle densities—0.93–1.18 g/cm^3 and 0.85 g/cm^3, respectively. Therefore, liquids with lower densities might be needed for achieving accurate results. The low density of liquid allows particles to completely sink, which otherwise would float in water. Weindorf & Wittie, (2003) used hexane for the particle density analysis of dairy manure compost because of its low density (0.66 g/cm^3).

The past studies have been found to be focused on determining the average particle density of manure solids rather than the particle densities of solids of individual diameter groups. Identifying the particle densities of individual solids in dairy manure will be more helpful while designing manure storage systems. Based on the standard method ASTM (1968), Bohnhoff & Converse (1987) determined the mean particle density of manure by grinding and mixing all solids present in manure. However, this method does not allow for the determination of particle density of individual groups of flushed manure solids with different diameters. For this, the manure solids need to be fractionated first, and a weighted average density of individual groups of particles would provide a better estimation of the overall particle density of flushed manure solids.

2.4.2 Past studies on the particle density of flushed dairy manure

As previously mentioned, no studies could be found in the literature that investigated the particle density of flushed dairy manure. There have been a handful of studies investigating the particle density of fresh dairy manure in the past (Achkari-Begdouri and Goodrich, 1992; Bohnhoff & Converse, 1987; Hafez et al., 1974 as reported in Sutitarnnontr et al., 2014; Sobel, 1966 as reported in Achkari-Begdouri and Goodrich, 1992; Sutitarnnontr et al., 2014). These studies reported the particle density of fresh manure to be in the range of 1.24–1.84 g/cm^3.

However, the compositions of fresh and flushed dairy manures are different. The flushed dairy manure contains additional solids including spilled feedstuffs, bedding materials, and solids from recycled lagoon flush water thereby impacting the overall particle density. As no study is available in the literature regarding the particle density of flushed dairy manure, this study would provide valuable information to dairy farmers and developers of manure management and treatment technologies. Also, past studies investigated only the overall particle density of dairy manure. Solids in dairy manure are of different sizes, each having a different particle density. The information on the individual particle densities of such solids would be more valuable while designing and constructing manure storage and treatment systems.

2.5 Particle size distribution of flushed dairy manure

Different solid-liquid separation technologies remove particles of different sizes; filtration can only remove particles above a certain size, the solid-liquid separation in settling basins/sedimentation tanks depends on the settling velocities of solids, which in turn depends on solid sizes (Hjorth et al, 2011), and mechanical separators with screens can only remove solids greater than the pore sizes of screens. The particle size plays an important role in determining the efficiency of solid-liquid separation (Hjorth et al, 2011).

Particle size distribution (PSD) is a common method for establishing the particle size fractions present in manure. The PSD shows how solids are distributed in the manure, based on their sizes. The precise determination of particle size distribution in flushed dairy manure is difficult as manure composition and characteristics change regularly. García–Mesa et al. (2010) pointed out that particle size distribution is characteristic for each facility. Variation in the particle size distribution could be due to differences in feedstuff particle size, feed type, and digestive power of cows (Hjorth et al., 2011; Meyer et al., 2007). Microbial decomposition of organic fraction also changes the particle size distribution of manure because of the conversion of organic compounds to carbon dioxide (CO_2), methane (CH_4), and aqueous ammonium (NH_4^+) (Christensen & Sommer, 2013; Hindrichsen et al., 2006; Hjorth et al., 2011).

2.5.1 Method for determination of particle size distribution of flushed dairy manure

For domestic, municipal, and industrial wastewaters, wet sieving, resonance mass measurement, electrolyte resistance, sequential ultra/nanofiltration, laser diffraction, particle image analysis, high-performance chromatography, and size exclusion chromatography are some commonly adopted methods for analyzing the constituents and their distributions (Arimi, 2018). However, the method for determining the PSD of livestock manure has not been standardized, and therefore, Christensen & Sommer (2013) argued that the characterizations of biowaste particles are arbitrary.

Most prior research on livestock manure PSD (Fernandes et al., 1988; Gilbertson et al., 1987; Hegg et al., 1981; Meyer et al., 2004; Meyer et al., 2007; Møller et al., 2002; Peters et al., 2011; Powers et al., 1995; Wright, 2005; Wu & Zhong, 2020) has been conducted using the ASTM D6913/D6913M-17 standard method involving wet sieve analysis (ASTM, 2017a). The other methods including different light scattering techniques for the determination of the PSD of livestock manure are also available, but they face several complications during the measurement because of the large particle size distribution and irregular structure of manure solids (Christensen & Sommer, 2013). The ASTM D6913/D6913M-17 standard wet sieving method gives the particle size distribution of solids that are larger than the 75 microns (0.075 mm). Upon the review of literature, the finest particle size for which the particle size distribution was determined using the wet sieving method was found to be 0.02 mm by Wright (2005).

The past studies that used the wet sieving method for the PSD determination of livestock manure also differ from one another. Hegg et al. (1981), Fernandes et al. (1988), Powers et al. (1995), and Peters et al. (2011) sprayed water slowly over the samples until all the particles in manure that would pass through the top screen had flowed through. Møller et al. (2002) used a water-jet sieving device with a spraying arm with nozzles to spray water at pressure, Meyer et al. (2004), Meyer et al. (2007), and Wright (2005) used vacuum-assisted wet mechanical sieving analysis with gentle stirring and rinsing with water to determine the PSD of raw dairy manure. Christensen & Sommer (2013) proposed sprinkling of recycled liquid manure to facilitate the transfer of solids through sieves during the wet sieving method.

However, as the standard wet sieving method only gives the particle size distribution of solids larger than 0.075 mm, the full profile of solids in liquid dairy manure cannot be determined using this method only. Also, different methods of wet sieving analysis adopted by past researchers can be a challenge if the goal is also to study the nutrient distribution. Sprinkling recycled lagoon liquid manures can add additional finer particles present in recycled liquid manure, thereby impacting the overall particle size and nutrient distribution. Using fresh water for facilitating the passage of solids through the screens would also not be appropriate as it would interfere with the nutrient concentrations.

Therefore, there is a need for a new method to establish the complete profile of solids in flushed dairy manures and link the nutrient contents with particle size distribution. This study adopted a new technique for linking the particle size and nutrient distribution of flushed dairy manure which is discussed in Chapter 3.

2.5.2 Past studies on the particle size distribution of flushed dairy manure

The particle size distribution of dairy manure has been studied by several researchers in the past. However, most of those studies have been on raw or fresh dairy manure. Previous studies on fresh manure have reported that most of the solids in raw manure are smaller than 0.5 mm in diameter.

Chang & Rible (1975), as reported in Zhang & Westerman (1997), found 41.8%, 7.1%, 7.2%, 3.9%, 2.0%, and 38.0% of TS present in fresh dairy manure belonging to 1-, 0.5-, 0.25-, 0.105-, 0.053-, and <0.053-mm diameter groups, respectively. The authors found about 51.1% of TS belonging to <0.5 mm diameter group. Powers et al. (1995) observed an average of 14.66%, 9.40%, 2.84%, 4.30%, 8.61%, and 60.21% of TS belonging to the 3.35-, 2-, 1.4-, 1-, 0.5-, and <0.5-mm sieve sizes, respectively in fecal samples of dairy cows. Wright (2005) found comparatively higher percentage of larger solids in fresh dairy manure. The author reported about 78% of TS >0.005 mm, 63% >0.6 mm, and 51% >2.5 mm.

Meyer et al. (2007), based on their study on the particle sizes in fresh dairy manure of lactating cows, reported the percent of solids belonging to 2-, 1-, 0.5-, 0.25-, 0.125-, and <0.125-mm to be about 30%, 7%, 6%, 5%, 3%, and 50%, respectively. Peters et al. (2011) also observed similar findings: about 59.2% of TS <0.025 mm in cattle slurry. Christensen & Sommer (2013) also posited that the amount of dry matter below 0.025 mm in a dairy slurry is about 50-55% of the total dry matter contained in the slurry. Wu & Zhong (2020) were the latest to study the PSD of fresh manure of lactating cows. They reported about 12.68%, 15.11%, 19.36%, and 52.85% of total solids belonging to the 1-, 0.5-, 0.15-, and <0.15-mm diameter groups, respectively.

However, due to the differences in the compositions of raw and flushed dairy manure, the particle size distribution of raw manure cannot be applied for flushed dairy manures. The flushed dairy manure contains additional solids including spilled feedstuffs, bedding materials, and solids from recycled lagoon flush water. Compared to fresh dairy manure, very little attention has been found to be given toward understanding the particle size distribution of flushed dairy manure. Upon review of the literature, two studies by Meyer et al. (2004) and Wright (2005) were found to be the only studies concerning the determination of particle size distribution of flushed dairy manure.

In the study by Meyer et al. (2004), the dairy used wash water from the milking parlor to flush the manure off the barn. The authors found about 10.48%, 12.26%, 13.80%, 14.27%, 18.28%, and 30.90% of total solids retained on sieves of 2-, 1-, 0.5-, 0.25-, 0.125-, and <0.125-mm pore-sized screens. The dairy investigated by Meyer et al. (2004) used wash water for flushing the alleyways. Some modern dairies use the recycled lagoon flush water for flushing to conserve water and increase the utility of liquid manure. The solids from the recycled flush water can alter the particle size distribution, and therefore, the use of PSD of flushed dairy manure with fresh water would not be reliable for approximating the PSD of flushed dairy manure.

A study by Wright (2005) was the only study that investigated particle size distribution of flushed dairy manure involving recycled lagoon flush water, and the author found a comparatively lower percentage of larger solids (about 20% of TS >1 mm) compared to dairies that used fresh water for flushing which could be due to the addition of finer solids contained in the recycled lagoon flush water.

Except for the study by Wright (2005), no other studies have looked at PSD of flushed dairy manure using recycled lagoon water as flush water. As more dairy farms are being attracted toward the flush system for manure removal, more studies on the particle size distribution of flushed dairy manures having different TS contents under varying dairy management practices would enhance the body of information in this field. The information would allow dairymen to make informed decisions regarding manure handling and implementation of effective solid-liquid separation technology in their farms.

2.6 Nutrient distribution of flushed dairy manure

The information on nutrients and their associations with solids of different particle sizes is important while assessing the non-homogeneity of the stored livestock slurry (Christensen & Sommer, 2013). Wright (2005) argued that the information on the variation of nutrients with particle sizes would be useful in modeling nutrient transport and fate. According to Peters et al. (2011), the knowledge of N and P distribution of animal slurry could help to better understand specific allocation and possible behavior of those nutrients during future utilization. Developing a nutrient distribution profile of flushed dairy manure would help farmers implement better nutrient management plans in their farms.

2.6.1 Method for determining the nutrient distribution of flushed dairy manure

The method for linking the nutrient distribution of livestock manure with particle size is not well defined, especially for finer manure solid particles. Most past research, including studies by Powers et al. (1995), Meyer et al. (2007), and Wu & Zhang (2020) relied on the wet sieving method to determine the nutrient content associated with solid particles larger than the pore size of the finest sieve. The finest particle size for which the nutrient distribution was determined was found to be 0.15 mm, reported by Wu & Zhang (2020). The studies on the distribution of nutrients associated with finer particles in dairy manure are lacking.

The standard ASTM D7928-17 method for sedimentation using the hydrometer analysis (ASTM, 2017b) is the commonly used method to determine the particle size distribution of soils smaller than 0.075 mm. Bouyoucos (1930) had opined that the hydrometer analysis method and the pipette method are equivalent in the determination of particle size distribution of soils, and Elfaki et al. (2016) also found no statistical differences between the results of the two methods. Therefore, Hellman & McKelvey (1941) had introduced a combined hydrometer-pipette method to determine the particle size distribution of soils which provided results similar to the results of the hydrometer method. This indicated that the nutrient distribution of finer solids could be linked to the particle size distribution by combing the hydrometer and pipette methods when the samples during the pipette method are recorded at the same time intervals as the recording of hydrometer readings during the hydrometer method.

However, no studies were found to adopt the technique as the past research relied on the standard wet sieving method (which only gives the distribution of nutrients associated with solids larger than 0.075 mm) to look at the distributions of nutrients in dairy manure.

2.6.2 Past studies on the nutrient distribution of flushed dairy manure

There have been very few studies investigating the nutrient distribution of dairy manure, and almost all of them have been made on raw/fresh dairy manure. The studies on raw dairy manure indicate that most of the nutrients in dairy manure are associated with finer solids.

Powers et al. (1995) observed an average of 86.29% TN and 94.33% TP present in feces of dairy cows associated with solid particles smaller than 0.5 mm. Similarly, Møller et al. (2000) posited that only about 5-7% of the TP are associated with solids greater than 0.5 mm. Meyer et al. (2007) also reported about 86% of TN and 85% of TP in fresh dairy manure to be associated with particle sizes smaller than 0.125 mm. The authors estimated that mechanical separators with a single 1.5-mm pore-sized screen could remove a maximum of 5% and 5% of TN and TP, while two-phase mechanical separators with 2- and 1-mm screen pore sizes would remove 7%, and 7% of TN and TP at maximum. Wu & Zhong (2020) also found most of the TN and TP in fresh manure of lactating cows to be associated with solids smaller than 0.15 mm.

However, the compositions of fresh manure and flushed manure are different; therefore, the nutrient distributions of raw manures cannot be applied for flushed dairy manures. Wright (2005) is the only study available in the literature that studied the particle size distribution and nutrient distribution of flushed dairy manure with a recycled lagoon flush water system. The author opined that the nitrogen content of flushed dairy manure varies with particle size but did not report the nutrient distribution data and suggested a need for further investigative studies on the nutrient distribution of flushed dairy manure.

As modern intensive dairies are being attracted toward a flush system for manure removal, it is important to understand the distribution of nutrients in flushed dairy manures. The knowledge of nutrient distribution is critical for dairy farmers to make informed decisions while devising and implementing better nutrient management plans for their dairy operations. Therefore, this work would fill the literature gap on the nutrient distribution of flushed dairy manure.

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Chapter 3: Research Methods

This chapter presents the research methodology adopted for the study. First, the sites selected for the study are briefly discussed. Then, the study parameters and the method of sample collection are introduced. The procedures adopted for studying the different parameters of the collected samples are then described in detail. The chapter concludes with brief information about the statistical tool used for data analysis.

3.1 Study sites

Four commercial dairies—Dairy #1, Dairy #2, Dairy #3, and Dairy #4—located in the Magic Valley region of Southern Idaho, USA were selected as case studies for the study. The Magic Valley region was selected for the study as it is the heart of Idaho's dairy production, accommodating about 70 percent of the state's dairy cows (Salant et al., 2017). All four commercial dairies had a centralized receiving pit where flushed manure entered and was pumped to primary and secondary treatment systems and then to a lagoon. The bedding material for all four dairies consisted of chopped hay and separated solids from their mechanical solid-liquid separators. The bedding was inspected every 2-4 days and replaced if necessary. The recycled lagoon water was used to flush the alleyways in dairies, #1, #2, and #4, while Dairy #3 used wash water from the milking parlor for dilution. About 7,000–10,000 gallons of flush water were used to flush each lane each time. The lanes were flushed three times a day at 8 h intervals.

3.1.1 Farm descriptions

3.1.1.1 Dairy #1

Dairy #1 was an open lot dairy with about 7,500 Holsteins. The dairy farm utilized a gravity-fed flushing system that removed dairy manure from alleyways and transferred the flushed dairy manure through small canals to a centralized receiving pit. After the liquid manure in the receiving pit reached the desired level, it was pumped to a primary set of inclined screen separators of 0.8 mm pore size. The separated solid particles were then used as bedding material for the dairy cows. The separated liquid portion then traveled through a raceway where it entered a pit before being pumped over the second set of inclined screen separators with a screen pore size of 0.5 mm. The separated solid particles were used for composting which was later spread out on the farmland adjacent to the dairy where alfalfa and corn were produced to feed the dairy cows. Part of the separated liquid manure was then recycled as flushing water. The separated liquid manure that was not utilized for flushing was sent to the open lagoon system for storage. The liquid wastewater from lagoons was used for fertilizing and irrigating fields (by mixing with irrigation water) during the cropping seasons. Figure 3.1 shows the Flow chart of manure management in Dairy #1.

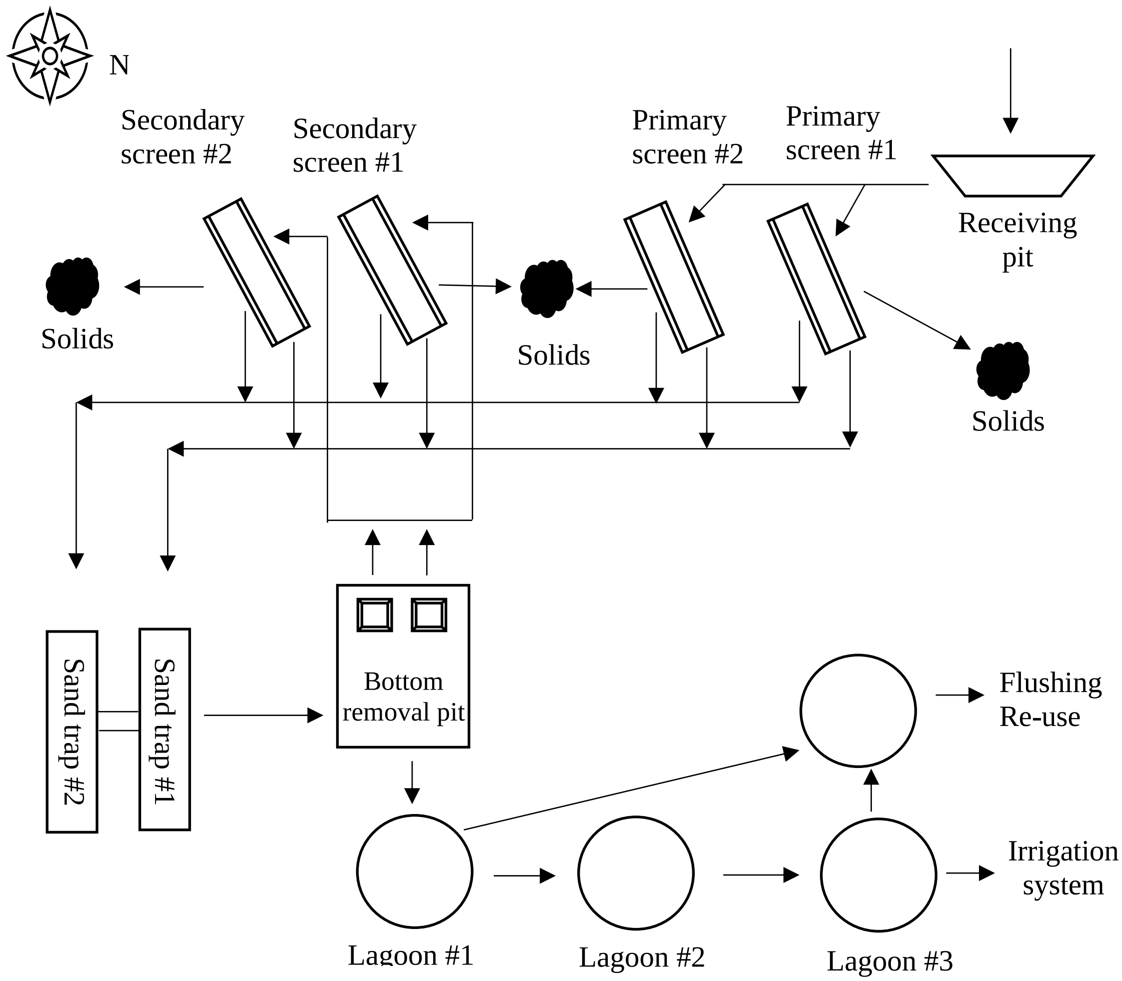

Figure 3.1: Flow chart of flushed dairy manure management in Dairy #1.

3.1.1.2 Dairy #2

Dairy #2 had a hybrid dairy housing system—both open lots and freestall barns—with about 4,800 milking cows. The dairy farm also utilized a gravity flushing system to remove dairy manure from the lanes behind feed alleys and transfer it to a centralized receiving pit. From the receiving pit, the flushed manure underwent primary solid-liquid separation via two screen separators of 0.8 mm screen pore size. The removed coarser solids were used for bedding purposes, while the liquid fraction was subjected to secondary solid-liquid separation via a centrifuge after temporarily storing in a bottom removal pit. After further removal of solids by the centrifuge, the liquid wastewater was stored in a flush pit and recycled for flushing purposes. The excess wastewater from the flush pit was stored in open lagoons before applying to fields. The flow chart of the flushed dairy manure handling system in Dairy #2 is shown in Figure 3.2.

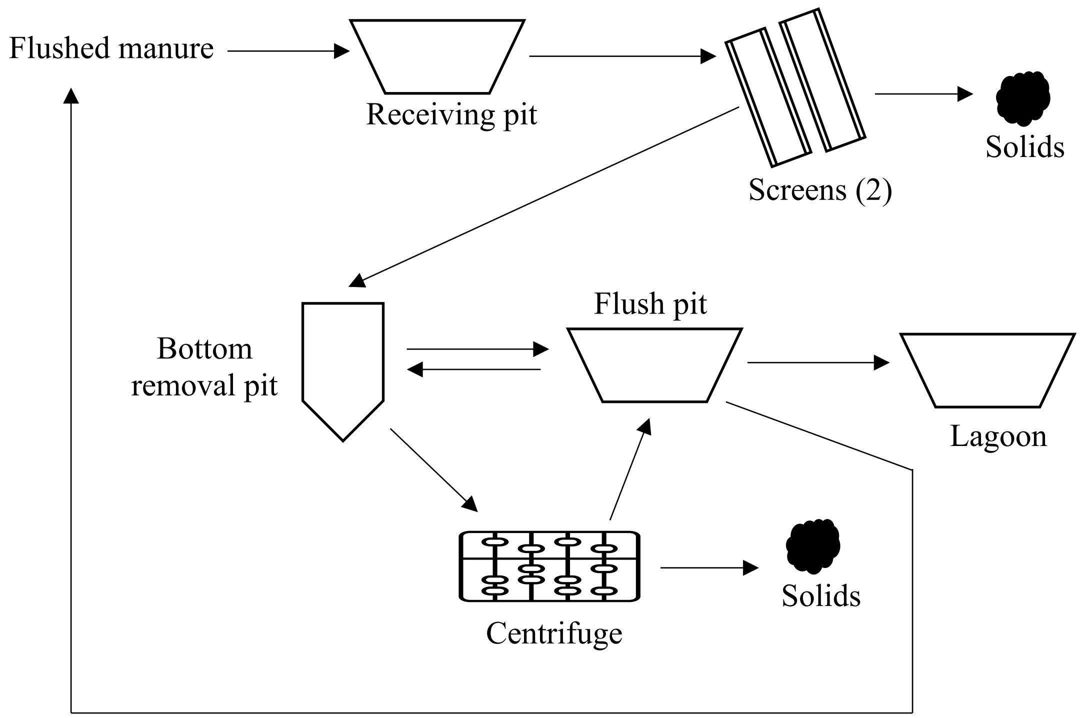

Figure 3.2: Flow chart of flushed dairy manure management in Dairy #2.

3.1.1.3 Dairy #3

Dairy #3 had cross-ventilated freestall barns that housed nearly 13,000 milking cows. The dairy farm used a scrape and vacuum method for removing manure from alleyways. Like other dairies, Dairy #3 also used separated solids and chopped hay as bedding material. The bedding material was inspected twice a week and changed if necessary. The alleyways were vacuumed by a Mensch vacuum truck twice a day. The vacuum truck had wash water from the milking parlor filled to a specified level to increase the dilution of manure after vacuuming. The vacuum truck dispersed the liquid manure into a receiving pit where more wash water from the milking parlor was added for further dilution. The liquid manure from the receiving pit was then transferred down the sand lane into an intermediate pit. The purpose of the sand lane was to drop off as much sand as possible along the way. The sand lane was cleaned twice a day. After temporary storage on the intermediate pit, the liquid manure underwent two-step solid-liquid separation: two inclined screen separators with a 0.5 mm pore size for primary treatment and two centrifuges for the secondary treatment. Separated solids from screens were composted, and about 25% of the composted solids were used as bedding, and the remaining 75% were applied to fields or transported off-site. The liquid fraction from the screens was then pumped to a pit before entering the centrifuges for secondary treatment. The separated solids from centrifuges were very thick and dense with high fine sand content which were transported to nutrient-depleted fields for application. The liquid fraction obtained from the centrifuge was then pumped to and stored in open lagoons from where the liquid manure was applied to agricultural farmlands. The lagoon wastewater was not recycled on the farm.

The dairy did not use the actual flush system, and consequently, the manure was technically not the flushed manure. Nevertheless, as the manure consisted of all components of flushed dairy manure (including feces, bedding material, animal hairs, wasted feedstuff, spilled drinking water, and wash water from milking parlor), the manure from this dairy was treated as the flushed manure for this study. Figure 3.3 shows the flow chart of the flushed dairy manure handling system in Dairy #3.

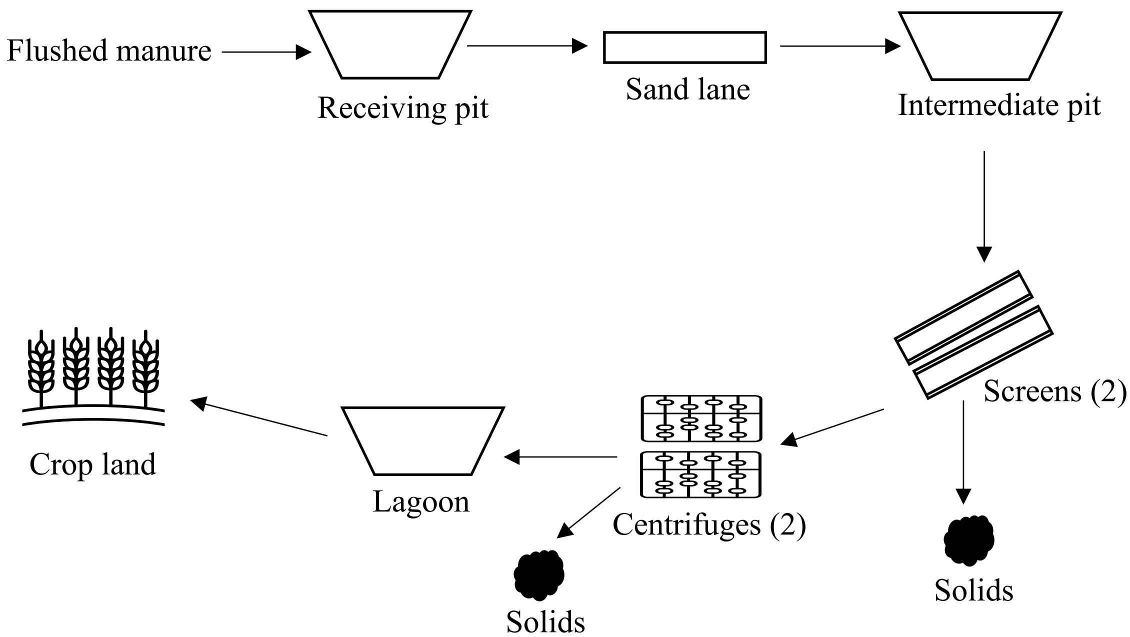

Figure 3.3: Flow chart of flushed dairy manure management in Dairy #3.

3.1.1.4 Dairy #4

Dairy #4 used a freestall barn housing system with approximately 13,000 dairy cows. The dairy used a flushing system to remove manure out of the barn into a centralized receiving pit. The dairy had an anaerobic digester for decomposing manure solids. After digestion, the effluent from the digester was subjected to solid-liquid separation. Like Dairy #1, Dairy #4 used 2 screen separators to fractionate solid and liquid fractions of the digester effluent. The primary screen separator had a screen pore size of 0.8 mm, while the secondary screen separator had a screen pore size of 0.5 mm. The solids separated from the two separators were used for bedding purposes. The liquid fraction was recirculated on the dairy farm as flush water. The excess liquid wastewater was temporarily stored in lagoons before application onto agricultural lands. The flow chart of the flushed dairy manure handling system in Dairy #4 is shown in Figure 3.4.

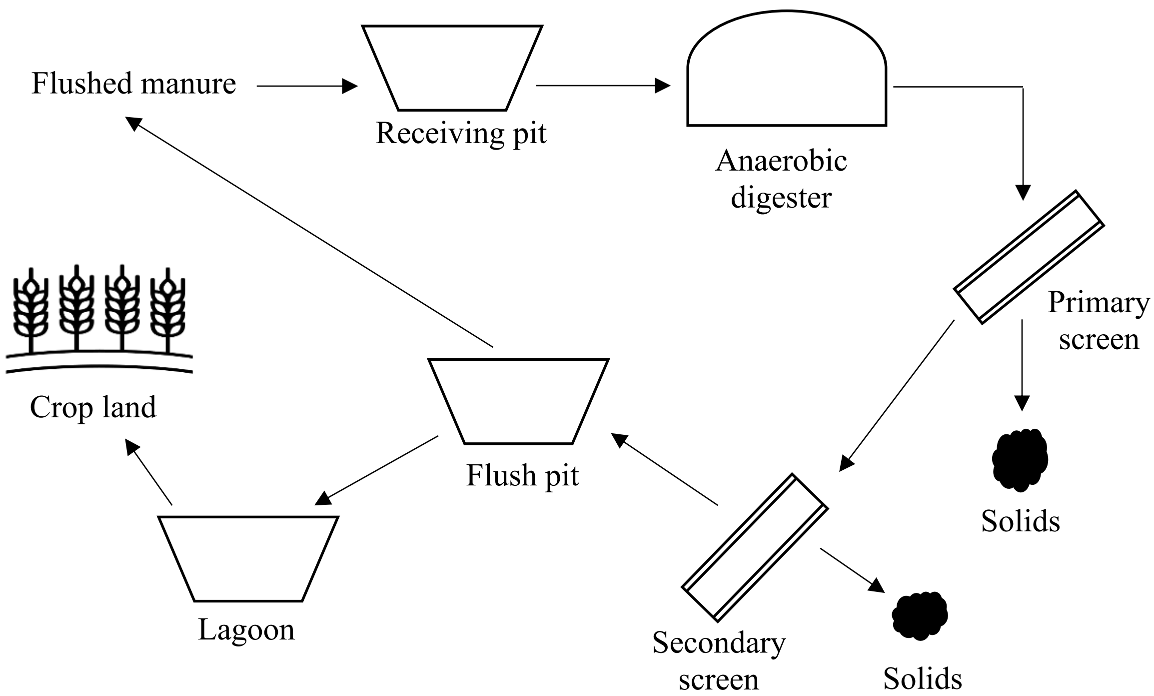

Figure 3.4: Flow chart of flushed dairy manure management in Dairy #4.

3.2 Study parameters

The flushed dairy manure samples were analyzed for the following parameters.

1. Initial total solids (TS)
2. Initial nutrient contents (total nitrogen and total phosphorous)
3. Particle density
4. Particle size distribution (PSD)

5. Cumulative particle size distribution
6. Nutrient (total nitrogen and total phosphorous) distribution
7. Cumulative nutrient total nitrogen and total phosphorous) distribution

3.3 Sample collection

Flushed dairy manure samples (n=3) were collected from the receiving pits of the four commercial dairies in the afternoon. The manure samples were drawn out of the receiving pits with the help of a bucket tied to a rope. After the bucket was pulled upward, the liquid manure was poured into a plastic jug with the aid of a funnel. The process was repeated to obtain three samples. The pumps were running, and the flushed manures were well agitated during the time of sample collection for maintaining homogeneity between the collected samples. Solids settled out of the liquid dairy manure quickly in the bucket. Therefore, to achieve homogenous mixing, the bucket was swirled vigorously before pouring the liquid manure samples into the plastic jugs. The jugs were then transported to the University of Idaho Waste Management Laboratory in Twin Falls and placed into a refrigerator at 4°C before analysis. The sample collection and experimental analysis were done between July and October of 2020.

3.4 Sample analysis

3.4.1 Initial total solids

The initial total solids (TS) present in flushed dairy manure for the four dairies were analyzed using the standard method 2540B (Baird et al., 2017). During this method, first, 0.5 L of flushed dairy manure samples were taken in aluminum pans from each of the 5-gallon plastic jugs in triplicates. The pans were then placed into an oven at 105°C for 48 hours for drying with regular monitoring to prevent the burning of manure solids. The standard time for the method is 24 hours, but the method was altered from the original method so that the 0.5 L volume of liquid dairy manure could completely dry to a constant weight. The weight of individual pans, combined weight of pans and wet samples, and combined weight of pans and dried samples were recorded during the experiment to calculate the total solids content.

The initial total solid concentrations present in the liquid dairy manure samples were calculated using Equation 3.1.

$$TS_c = \frac{W_{d+P} - W_p}{V_s} \qquad \text{Equation 3.1}$$

where TS_c is the initial total solid concentration (g/l) present in liquid dairy manure samples, W_p is the mass (g) of the aluminum pan, W_{d+p} is the combined mass (g) of the dried solids and aluminum pan, and *Vs* is the volume (L) of the sample taken.

The initial total solid contents were then determined using Equation 3.2.

$$TS = TS_c \times V_i \qquad \text{Equation 3.2}$$

where *TS* is the quantity of initial total solids (g) present in liquid dairy manure samples, TS_c is the initial total solids concentration (g/l), V_i is the initial volume (L) of liquid manure taken for wet sieving analysis.

The initial percent of total solids in the liquid manure samples were calculated from Equation 3.3.

$$TS\% = \frac{W_{d+p} - W_p}{W_{w+p} - W_p} \times 100 \qquad \text{Equation 3.3}$$

where *TS%* is the initial percentage of solids in liquid dairy manure samples, W_p is the mass (g) of the aluminum pan, W_{w+p} is the combined mass (g) of wet sample and aluminum pan, and W_{d+p} is the combined mass (g) of the dried solids and aluminum pan.

3.4.2 Initial nutrient content

The nutrient initial contents, total nitrogen (TN) and total phosphorous (TP) in flushed dairy manures of the four dairies were analyzed as per the Hach methods using a spectrophotometer (DR5000, Hach, USA). The Hach methods used for total nitrogen and total phosphorous analyses were TNT 880 and TNT 845, respectively. The Hach methods give nutrient concentrations in mg/l. To find the initial masses of nutrients in the flushed dairy manure samples, thus obtained nutrient concentrations were multiplied by the initial volume of flushed dairy manure taken for the wet sieving analysis.

3.4.3 Particle density

The particle densities of flushed dairy manure solids were determined according to the standard method ASTM D854-14 Method B using a pycnometer (ASTM, 2014), but with a methanol medium instead of distilled water as some manure particles are lighter than water and will not settle out of suspension thereby compromising the accurate measurement of displaced volume (Weindorf & Wittie, 2003). Particle density was calculated for solids of particle diameters 4-, 2-, 0.5-, 0.25-, 0.125-, 0.063-, and <0.063-mm within the liquid dairy manure. The solids for the pycnometer test were obtained from the dried mass retained on each sieve during the wet sieving method (Figure 4.2). Due to the small quantity of solids obtained for some particle diameter groups, multiple batches of the wet sieving method were conducted to obtain enough mass for the particle density analysis.

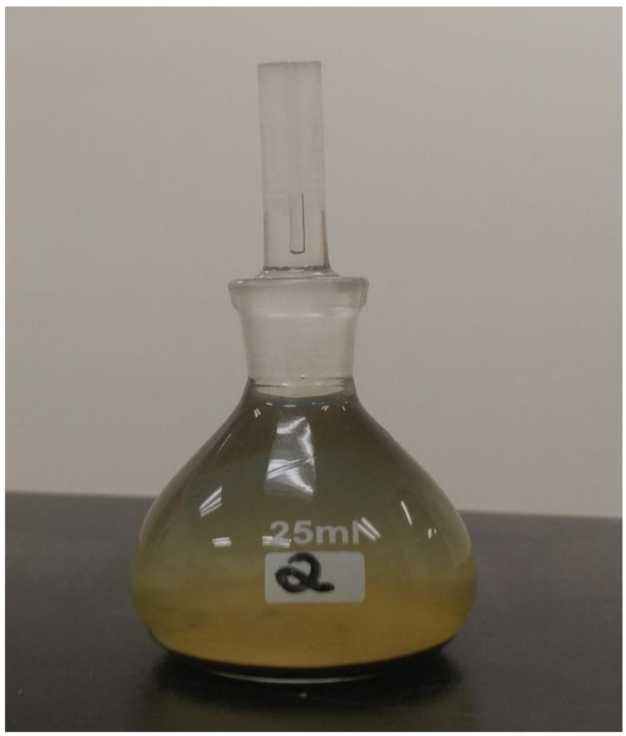

Figure 3.5: Particle density analysis by the pycnometer method.

The procedure of the particle density analysis using a pycnometer (Figure 3.5) adopted in this study is as follows. First, the pycnometer was weighed to find the mass of the individual 25 cm^3 pycnometer apparatus and stopper. Then, 0.6 g of the solids belonging to a specific particle diameter group (4, 2, 0.5, 0.25, 0.125, 0.063, and <0.063 mm) were introduced into the pycnometer using a funnel. The combined mass of the pycnometer apparatus, stopper, and dry particle matter was weighed and recorded. The pycnometer was then filled halfway with methanol to get all the particles off the walls. Afterward, the pycnometer was filled with methanol to the top. The stopper with a hollowed-out center allowed for the displacement of methanol retaining an exact 25 cm^3 volume inside the pycnometer. The liquid methanol coming out of the hollowed stopper was soaked using a tissue to keep the outside of the pycnometer moisture-free. Then the combined mass of pycnometer apparatus, stopper, methanol, and particle was recorded. The pycnometer apparatus was then emptied, thoroughly rinsed, and dried. When dry, only methanol was added to the pycnometer apparatus and again weighed to record the combined mass.

Equation 3.4 (from Weindorf & Wittie, 2003) was used to calculate the particle density of solids of each particle diameter group obtained during the wet sieving process.

$$\rho_p = \frac{\rho_m \times W_s}{W_s - (W_{s+m} - W_m)} \qquad \text{Equation 3.4}$$

where ρ_p is the particle density of solids of specific particle diameter, ρ_m is the density of methanol (0.792 g/cm^3 at 20°C from NCBI, 2021), W_m is the mass (g) of methanol, W_s is the mass (g) of oven-dried solids of specified particle diameter, and W_{s+m} is the combined mass (g) of solids and methanol inside the pycnometer.

Equation 3.4 calculates the particle densities of solids belonging to different diameter groups. For calculating the average particle densities of flushed dairy manures of the four dairies, the weighted average method was used unlike Bohnhoff & Converse (1987), who crushed and mixed all the fractionated solid particles. The dried solids needed to be preserved for demonstration for extension programs. Therefore, after the calculation of individual particle density of solids of different diameters groups, the average particle density of flushed dairy manure solids for each dairy was calculated by taking the weighted average of particle densities of seven different particle diameter groups (4, 2, 0.5, 0.25, 0.125, 0.063, and <0.063 mm) using Equation 3.5.

$$\rho_{avg} = \frac{\sum_{d=4}^{<0.063} \left(\%PR_n \times \rho_p\right)}{100} \qquad \text{Equation 3.5}$$

where ρ_{avg} is the weighted average particle density (g/cm^3) of flushed dairy manure solids for a dairy, $\%PR_n$ is the percentage of solids belonging to diameter groups from 4 to <0.063 mm (obtained from Equation 3.6), and ρ_p is the particle density of solids belonging to particle diameters from 4 to <0.063 mm in g/cm^3 (obtained from Equation 3.4).

3.4.4 Particle size distribution

Due to the lack of a standard method for the determination of particle size distribution of livestock manure, two commonly used methods of PSD determination for soils—wet sieving analysis and hydrometer analysis—were combined to quantify particle size distributions of the flushed dairy manures of the four dairies in this study. The standard ASTM D7928-17 method for sedimentation using the hydrometer analysis (ASTM, 2017b) is the commonly used method to determine the particle size distribution of soils smaller than 0.075 mm. For this study, the distribution of coarser solids above 0.063 mm was determined by the wet sieving analysis method, while that of finer solids below 0.063 mm was determined using the standard ASTM D7928-17 hydrometer analysis method as per the laboratory manual of Das (2002). The findings of wet sieving and hydrometer methods were then combined to obtain a full profile of solids i. e. PSD in flushed dairy manure.

3.4.4.1 Wet sieving analysis

During this method, six stainless steel wire sieves having pore diameters of 4-, 2-, 0.5-, 0.25-, 0.125-, and 0.063-mm were used to fractionate solids >0.063 mm from the liquid manure samples. Particle size fractioning was performed by passing known volumes of liquid dairy manure samples progressively through six sieves.

Figure 3.6: Arrangement for the wet sieving analysis.

The arrangement for the wet sieving analysis (Figure 3.6) consisted of a single specified diameter sieve (4 mm first) mounted on an 8-inch funnel which was placed on top of a 5L flask and fixed by a stopper. Measured volumes of liquid manure samples were then poured manually over the surface of the sieve in a circular motion with gentle stirring by a stirring rod. The circular motion allowed liquid manure to be spread on the entire surface of the sieve so that smaller particles could easily pass through and not get attached to larger particles on the sieves. The liquid in the flask that passed through the first sieve was then poured into the next sieve-funnel-flask arrangement (with a sieve pore diameter of 2 mm). The procedure was then repeated for the remaining four sieves. A single run of the sieving process took approximately three hours to complete. Figure 3.7 shows the representative samples of solids retained on each sieve during the process.

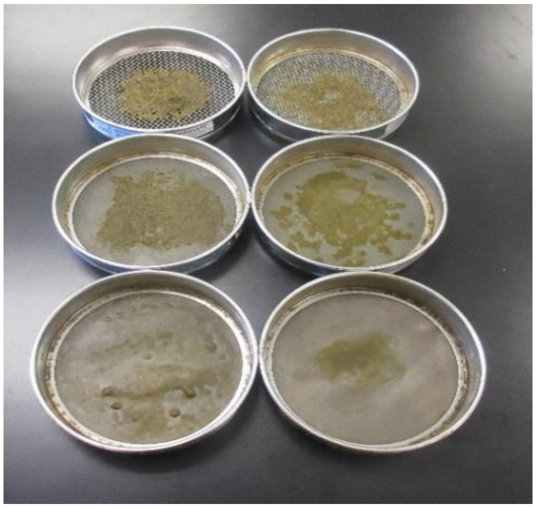

Figure 3.7: Solids retained on the six sieves during the wet sieving analysis: Top left = 4 mm, top right = 2 mm, center left = 0.5 mm, center right = 0.25 mm, bottom left = 0.125 mm, and bottom right = 0.063 mm.

3.4.4.1.1 Percent retained solids

The solids retained on each sieve were then transferred to aluminum pans using deionized water. The aluminum pans were placed in an oven at 105°C for 24 hours, cooled in a desiccator, and weighed on an analytical balance. The dried mass (Figure 3.8 and Figure 4.2) retained on each sieve (known and calculated as retained solids) represents a fraction of the total solids contained within the liquid dairy manure sample, and each sieve represents a mean size fraction of the specific particle diameter.

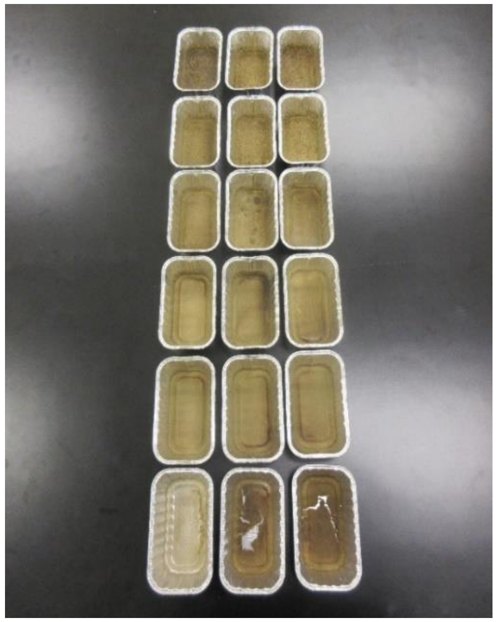

Figure 3.8: Oven-dried solids retained on the six sieves during the wet sieving analysis: 4 mm, 2 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm from top to bottom.

The percent retained solids on each sieve were then calculated using Equation 3.6.

$$\%PR_n = \frac{DS_n}{TS} \times 100 \qquad \text{Equation 3.6}$$

where $\%PR_n$ is the percent solids retained on the sieve of diameter n, DS_n is the dried solid mass (g) retained on the sieve of diameter n, and TS is the initial total solids (g) present in the initial volume of liquid dairy manure taken for wet sieving analysis (obtained from Equation 3.2).

The dried masses of solids retained on sieves were calculated according to Equation 3.7.

$$DS_n = W_{p+s} - W_p \quad \text{Equation 3.7}$$

where DS_n is the mass (g) of dried solids retained on the sieve of diameter n, W_p is the mass (g) of the aluminum pan, and W_{p+s} is the combined mass (g) of the pan and dry solids.

3.4.4.2 Hydrometer analysis

The wet sieving procedure reduced the particle diameters within the liquid dairy manure to a size smaller than 0.063 mm. The hydrometer analysis method (Figure 3.9) was then used to determine the particle size distribution of solids finer than 0.063 mm. After the sieving procedure, 1 liter of liquid dairy manure sample that passed through the 0.063-mm pore-sized sieve was taken in a graduated cylinder for sedimentation (hydrometer) analysis, resulting in three replications per dairy. The liquid manure temperature during the whole analysis period ranged from 16.5 to 19.5°C. An ASTM 152-H type hydrometer was used to analyze the specific gravity of suspended solids in the liquid dairy manure. The hydrometer was placed in each cylinder at time intervals 2, 15, 60, 250, 1440, and 2880 minutes and corresponding hydrometer readings were noted down. Manure temperatures were also recorded during the same time intervals using an H-B® B60302-0000 Easy-Read® general purpose liquid-in-glass thermometer. After each reading, the hydrometer was placed in a 1L cylinder of deionized water for storage before the next measurement. The meniscus, temperature, and density corrections were made to the recorded hydrometer readings as per the Das (2002) manual. Based on hydrometer readings, percent finers of solids below different diameter groups were determined which were then used to calculate the percentages of solids associated with different diameter groups observed during the hydrometer analysis method.

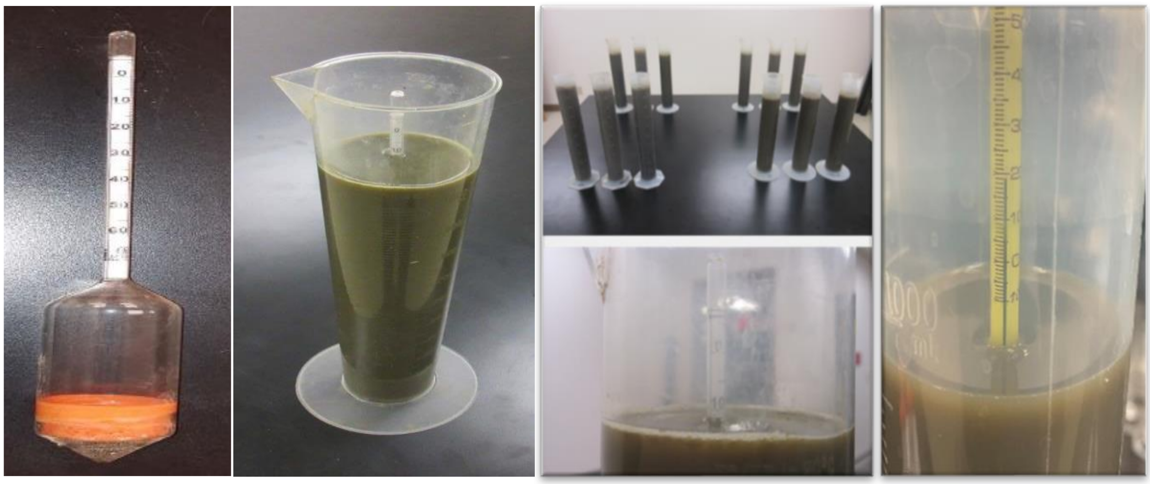

Figure 3.9: Hydrometer analysis method.

3.4.4.2.1 Particle diameters

The hydrometer method relies on Stokes' law to determine the particle diameters of finer solids (Das, 2002). When a hydrometer is inserted into a solid solution, it will measure the specific gravity of suspended solids at a depth L, also known as the effective depth. The effective depth is the length of the hydrometer from the meniscus to the center of the bulb of the hydrometer. According to Das (2002), at time t (in minutes) from the beginning of the test, the manure particles that settle beyond the effective depth zone of measurement will have a diameter given by Equation 3.8.

$$\frac{ED}{t \times 60} = \frac{(\gamma_s - \gamma_w)}{18 \times \eta} \times \left(\frac{d}{10}\right)^2 \quad \text{Equation 3.8}$$

where *ED* is the effective depth in cm, *t* is time in minutes, γ_s is the particle density of the manure in g/cm^3, γ_w is the particle density of water in g/cm^3, η is the viscosity of water in (g*s/cm^2) at 20°C, and *d* is the particle diameter in mm. The conversion factor of 60 converts minutes to seconds and 10 converts cm to mm. Since hydrometer readings were recorded at six different time intervals, a total of six particle diameters were determined during the process.

By solving Equation 3.8, particle diameters (d_1–d_6) of solids present in liquid manure can be obtained from Equation 3.9.

$$d_{1-6} = \frac{10}{\sqrt{60}} \times \sqrt{\frac{18 \times \eta}{(\gamma_s - \gamma_w)}} \times \sqrt{\frac{ED}{t}} \qquad \text{Equation 3.9}$$

The effective depth (*ED*) was calculated using Equation 3.10 (Das, 2002).

$$ED = L_1 + \frac{1}{2}\left(L_2 - \frac{V_B}{A_C}\right) \qquad \text{Equation 3.10}$$

where L_1 is the distance (cm) between the top of the hydrometer bulb to the meniscus for a given hydrometer reading, V_B is the volume of the hydrometer bulb at 67.0 cm^3, and A_C is the cross-sectional area of the hydrometer cylinder at 27.8 cm^2.

For an ASTM 152-H type hydrometer reading of zero, L_1 is equal to 10.5 cm, while for a hydrometer reading of 50 g/l, L_1 is 2.3 cm, and L_2 is the height of the hydrometer bulb at 14 cm for ASTM type hydrometer (Das, 2002). The L_1 for a specific hydrometer reading (H_r) could be calculated from Equation 3.11.

$$L_1 = 10.5 - \left(\frac{10.5 - 2.3}{50}\right) \times H_r \qquad \text{Equation 3.11}$$

The hydrometer method gives six different particle sizes at six readings, and the particle diameters observed would be different for different experiments and different dairies. To make comparisons between the four dairies easier, the particle diameters below 0.063 mm observed after each time interval during the hydrometer analysis method for the four dairies were averaged to come up with the same particle diameter.

3.4.4.2.2 Hydrometer reading corrections

The ASTM 152-H type hydrometer is calibrated for a particle density of 2.65 g/cm^3 to be measured at a temperature of 20°C. The temperature of liquid manures during the experiment ranged from 16-22°C. Therefore, some adjustments needed to be made to the observed hydrometer readings. The following corrections were needed to obtain accurate hydrometer readings based on Das (2000) manual.

1. Temperature correction (C_T):

The actual temperature of liquid manures during the experiments was different from the standard 20°C for the hydrometer analysis. Temperature correction to the observed hydrometer readings was made according to Equation 3.12.

$$C_T = -4.85 + 0.25 \times T \qquad \text{Equation 3.12}$$

where C_T is the temperature correction to the observed reading and T is the temperature of the test in °C.

2. Meniscus correction (C_M):

Generally, the upper level of the meniscus is taken as reading during laboratory experiments. To get the accurate hydrometer reading (bottom level of the meniscus), the hydrometer was first inserted into a measuring cylinder of distilled water, and the readings at the top and bottom of the meniscus were recorded. The difference between two meniscus levels provided the meniscus correction (C_M) which is a constant for a hydrometer.

3. Zero correction (C_Z):

Generally, deflocculating agents are used during the hydrometer analysis method, and therefore, zero corrections are required to account for the possible impact of those agents on hydrometer readings. However, because of possible interference during nutrient analysis, no deflocculating agents were used during this study. Therefore, this study did not require zero correction.

The temperature- and meniscus-corrected hydrometer readings (R_C) were then determined using Equation 3.13.

$$R_C = R + C_T + C_M \qquad \text{Equation 3.13}$$

where R is the observed hydrometer reading at any time t, C_T is the temperature correction, and C_M is the meniscus correction.

4. Density correction (C_D):

As mentioned earlier, the ASTM 152-H type hydrometer is calibrated for a particle density of 2.65 g/cm^3. The density of dairy manure and soil is different; therefore, density corrections are required for the temperature- and meniscus-corrected hydrometer readings. The density corrections were made using a density correction factor—C_D, which was calculated from Equation 3.14.

$$C_D = \frac{\rho_{<0.063} \times 1.65}{(\rho_{<0.063} - 1) \times 2.65} \qquad \text{Equation 3.14}$$

where C_D is the density correction factor for the hydrometer reading of liquid manure suspension and $\rho_{<0.063}$ is the average particle density (g/cm^3) of solids smaller than 0.063 mm obtained from Equation 3.4.

Finally, the corrected hydrometer reading (H_R) was calculated according to Equation 3.15.

$$H_R = C_D \times R_C \qquad \text{Equation 3.15}$$

For linking nutrients with the particle size distribution, 10 ml samples were drawn out after each hydrometer reading, which reduced the volume of the total sample by 10 ml each time. Therefore, the corrected hydrometer readings were adjusted to account for the volume reduction before calculating percent finer and particle diameters.

3.4.2.2.3 Percent finer

The direct measurement of the amount of solids of a particular diameter group present in the liquid manure during hydrometer analysis is difficult. It is therefore determined using the concept of percent finer. The percent finer is the percentage of solids still in suspension at a time (*t*) from the onset of the hydrometer test. The percent finer at a specific particle diameter (PF_n) represents the percentage of total solid particles that have diameters smaller than that particular particle diameter group d_n (obtained from Equation 3.9) and was calculated using Equation 3.16 as per Das (2002).

$$PF_n = \frac{H_R}{W_s} \times 100 \qquad \text{Equation 3.16}$$

where H_R is the corrected hydrometer reading (from Equation 3.15) and W_s is the dry mass (g) of solids present in 1 L liquid manure taken after sieving for the hydrometer test.

The dry mass of manure in the 1L volume of liquid manure that passed via 0.063 mm sieve (W_s) was calculated based on the difference of the total dry matter weight present in the initial volume of the sample taken during the wet sieving method and the sum of dry weights of solids retained on six sieves.

3.4.2.2.4 Calculation of percent solids from percent finer

The percent finer value itself is not the solids content associated with each particle diameter. The percent finer value is then used for determining the amount of solids associated with different particle diameters during the hydrometer analysis. The percentage of solid fraction associated with each particle diameter during the hydrometer analysis was determined from the difference of the percent finer of two separate diameter groups using Equation 3.17.

$$\%S_{d_n} = PF_{d_{n-1}} - PF_{d_{n_{n=2-6}}} \qquad \text{Equation 3.17}$$

where $\%S_{dn}$ is the percentage of solid fraction associated with a particular diameter d_n, PF_{dn} is the percent finer of solids whose diameter were d_n, and PF_{dn-1} is the percent finer of solids associated with diameter d_{n-1}.

Equation 3.17 does not calculate the amount of solids associated with the first particle diameter group (d_1). It was calculated using Equation 3.18.

$$\%S_{d_1} = 100\% - PF_1 \qquad \text{Equation 3.18}$$

where $\%S_{d1}$ is the percentage of solid fraction associated with the first particle diameter group (d_1) and PF_1 is the percent finer of solids associated with particle diameter d_1 (obtained from Equation 3.16).

Equation 3.17 and Equation 3.18 calculated the percentage of solids present in 1L liquid manure associated with different particle diameters <0.063 mm during the hydrometer method. To convert these values to percent solids of the initial total solids present in the known volume of liquid manure taken during the wet sieving analysis, Equation 3.19 was used.

$$\%S_n = \frac{\%S_{d_n} \times W_s}{TS} \times 100 \qquad \text{Equation 3.19}$$

where $\%S_n$ represents the percent solids (of initial solid content) belonging to different diameter groups observed during the hydrometer method, $\%S_{dn}$ is the percent solids associated with particle diameter d_n from the hydrometer method, W_s is the dry weight of manure (g) in a 1L volume of liquid dairy manure used for the hydrometer test, and TS is the total solids (g) in the initial volume of liquid dairy manure taken for wet sieving analysis.

Finally, the particle size distribution of solids present in flushed dairy manure was determined by combining the percent solids associated with different particle diameters during the wet sieving and hydrometer analysis methods (obtained from Equation 3.6 and Equation 3.19).

3.4.5 Nutrient distribution

As there has not been a standard method to link nutrient contents with finer particles in flushed dairy manures, a technique suggested by Hellman & McKelvey (1941)—the hydrometer-pipette method—was adopted for this study. During this method, the nutrient distributions (total nitrogen and total phosphorous distributions) of flushed dairy manures were determined by combining the nutrients associated with particles of different diameter groups from the wet sieving and hydrometer method. For this, first, the nutrient contents belonging to solids of different diameter groups were determined using the concept of mass balance. Then, the observed nutrient values were converted to the percentage of initial nutrient content.

Finally, the combined percentages of solids from wet sieving and hydrometer methods were taken to obtain a full nutrient distribution of the flushed dairy manures.

The liquid dairy manure samples were analyzed for total nitrogen (TN) and total phosphorous (TP) as per the Hach methods using a spectrophotometer (DR5000, Hach, USA) (Figure 3.10). The Hach methods used for nutrient analysis were TNT 880 for TN and TNT 845 for TP. The Hach methods provide nutrient concentrations in terms of mg/l. The corresponding masses of nutrients were determined by multiplying the observed nutrient concentration associated with solids of a particular diameter group by the volume of the liquid manure from which samples were drawn for nutrient analysis.

Figure 3.10: Total nitrogen and total phosphorous analysis using the Hach methods.

3.4.5.1 Determination of nutrient content associated with different diameters

For determining the nutrient contents associated with solids of different diameter groups during the wet sieving method, first, 10 ml liquid manure samples that passed through each sieve were taken out from the flask using a pipette after each passing. The samples drawn during the wet sieving were placed in vials and stored in a refrigerator at 4°C to await nutrient analysis. Then the difference between the nutrient values of samples before and after sieving was calculated to determine the amount of nutrients belonging to solids of each diameter group.

Equation 3.20 shows the calculation of nutrient content associated with solids of a particular diameter group during the wet sieving process based on the concept of mass balance.

$$NC_n = NC_{initial} - NC_{final} \qquad \text{Equation 3.20}$$

where NC_n is the nutrient content associated with solids of a particular diameter group (4 to 0.063 mm), $NC_{initial}$ is the nutrient content of the liquid dairy manure before each sieving and NC_{final} is the nutrient content of the liquid dairy manure after the sieving has taken place.

For determining the nutrient contents associated with solids of different diameter groups during the hydrometer analysis method, 10 ml liquid manure was carefully drawn out of the measuring cylinders using a pipette at the time of each hydrometer reading (2-, 15-, 60-, 250-, 1440-, and 2880- minutes). The samples were drawn from a fixed depth of 10 cm from the liquid manure surface. The samples drawn from hydrometer analysis methods were placed in vials where they would be stored in a refrigerator for no more than 7 days at 4°C to await nutrient analysis. After nutrient analysis, the nutrient concentrations were multiplied with the volume of liquid manure obtained after the sieving process to find the mass of nutrients associated with solids of a particular diameter group. The difference between the recorded values at two consecutive hydrometer readings provided the amount of nutrients belonging to solids of the corresponding diameter groups.

The nutrient contents (NC_{dn}) associated with solids of a particular diameter group d_n during the hydrometer method were determined using Equation 3.21.

$$NC_{d_n} = NC_{d_{n-1}} - N_{d_n} \qquad \text{Equation 3.21}$$

where N_{dn} is the observed nutrient content at particle diameter d_n and NC_{dn-1} is the observed nutrient content at particle diameter d_{n-1} during the hydrometer test.

Equation 3.21 does not calculate the nutrient content associated with solids of the first diameter group (d_1), which was calculated from Equation 3.22.

$$NC_{d_1} = N_{d_w} - N_{d_1} \qquad \text{Equation 3.22}$$

where NC_{d1} is the nutrient content associated with solids of particle diameter d_1, N_{d1} is the observed nutrient content associated with solids of diameter group of d_1 and N_{dw} is the total nutrient content present in the total volume of liquid manure that passed via the 0.063 mm sieve during sieving process.

3.4.5.2 Percent nutrient distribution

To find the percent nutrient distribution associated with solids of each diameter group for both the wet sieving and the hydrometer analysis methods, Equation 3.23 was used.

$$\%PN_{d_n} = \frac{NC_{d_n}}{NC_{initial}} \times 100 \qquad \text{Equation 3.23}$$

where $\%PN_{dn}$ is the percent nutrients associated with solids of each diameter group from the wet sieving and the hydrometer analysis methods, NC_{dn} is the nutrient content associated with solids of each particle diameter group during both methods, and $NC_{initial}$ is the initial nutrient content present in the volume of liquid manure taken for the wet sieving process.

Finally, the nutrient distributions of flushed dairy manures were determined by combining the percent TN associated with solids of different diameter groups observed during both wet sieving and hydrometer analysis methods.

3.5 Statistical Analysis

The calculations were carried out on Excel 2016, and statistical analyses were performed using the general statistical analysis module of the R statistical software package version 4.0.3.

The flushed dairy manures of the four dairies were compared for initial total solid and nutrient contents by one-way ANOVA, followed by the Tukey test for mean comparisons.

Since the percent solids and nutrients data were bounded between 0 and 1, a generalized linear model with beta (β) distribution (package "*betareg*" in R, Cribari-Neto & Zeileis, 2010) was used to examine the solid and total nutrient (TN and TP) removal capacities of different pore-sized inclined screen separators based on the cumulative percent of solids and nutrients that belonged to a particular diameter group (pore size). The solid and nutrient removal capacities of different pore sizes were compared using the *joint_tests* function in the *emmeans* package in R, followed by Tukey-adjusted pairwise comparisons as a post hoc test.

Finally, the particle densities of solids of different sizes were compared using a simple one-way ANOVA, followed by mean comparisons with the Tukey test.

As García-Mesa et al. (2010) had pointed out that the particle size distribution is characteristic for each facility, and the four dairies under this study also varied in the management practices, the dairies were analyzed individually for particle density of solids belonging to different diameter groups and solid and nutrient removal capacities of different pore sized inclined screen separators. p-value ≤ 0.05 was considered significant for all the analyses.

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Chapter 4: Results

This chapter presents the findings of the study including the results of statistical analyses.

4.1 Initial total solid content

Table 4.1 shows the initial total solid (TS) contents in the flushed dairy manures of the four dairies. The flushed manures of the four dairies varied in the initial total solid contents. The four dairies were found to be statistically different for initial total solid content. Dairy #4 had the highest TS (7.69±0.13%), followed by Dairy #2 (4.97±0.13%), Dairy #3 (4.42±0.09%), and Dairy #1 (2.23±0.08%).

Table 4.1: Initial total solid contents in flushed dairy manures of the four dairies.

Dairy	TS (g/l)	TS (%)
#1	25.96±1.03d	2.23±0.08d
#2	72.46±1.42b	4.97±0.13b
#3	61.86±0.58c	4.42±0.09c
#4	100.67±1.49a	7.69±0.13a

Note: Initial TS contents are presented as means (n=3) ± standard deviations. Dairies with different letters are statistically different from each other ($p<0.05$).

4.2 Initial nutrient content

The initial total nitrogen (TN) and total phosphorous (TP) contents of the flushed dairy manures of the four dairies are given in Table 4.2. Like TS, the initial nutrient contents in the flushed dairy manure of the four dairies differed significantly from one another. Dairy #4 had the highest percentages of TN and TP (0.193±0.002%, and 0.130±0.002%, respectively), while Dairy #1 had the lowest percentages of nutrients (0.079±0.013% TN and 0.043±0.001%TP) among the four dairies. The initial nitrogen content in Dairy #2 (0.132±0.005%) was higher than that of Dairy #3 (0.110±0.001%), while its initial phosphorous content was lower (0.071±0.003%) compared to Dairy #3 (0.080±0.001%).

Table 4.2: Initial nutrient contents (wet weight basis) in flushed dairy manures of the four dairies.

Dairy	TN (mg/l)	TN (%)	TP (mg/l)	TP (%)
#1	909.67±141.22d	0.079±0.013d	491.33±15.63d	0.043±0.001d
#2	1911.67±51.64b	0.132±0.005b	947.00±18.25c	0.071±0.003c
#3	1583.67±75.87c	0.110±0.001c	1117.00±5.29b	0.080±0.001b
#4	2554.67±41.40a	0.193±0.002a	1702.33±2.52a	0.130±0.002a

Note: Nutrient contents are presented as means (n=3) ± standard deviations. Dairies with different letters are statistically different from each other ($p<0.05$).

4.3 Particle density

The particle densities of flushed dairy manure solids were found to be closely related to particle size (diameter). The particle density decreased with the increase in particle size. Solids <0.063 mm in size had the highest particle density: 1.68±0.05 g/cm^3, 1.61±0.01 g/cm^3, 1.64±0.06 g/cm^3, and 1.62±0.01 g/cm^3 for dairies, #1, #2, #3, and #4, respectively. Likewise, solids >4 mm in size had the lowest particle densities: 0.83±0.04 g/cm^3, 0.88±0.07 g/cm^3, 0.88±0.04 g/cm^3, and 0.91±0.08 g/cm^3 for dairies, #1, #2, #3, and #4, respectively. The particle densities of solids of 2-, 0.4-, 0.25-, 0.125-, and 0.063-mm diameter ranged from 0.84±0.05 to 1.60±0.09 g/cm^3, 0.90±0.01 to 1.53±0.10 g/cm^3, 0.90±0.03 to 1.55±0.09 g/cm^3, and 0.94±0.02 to 1.37±0.13 g/cm^3 in the four dairies, respectively. Figure 4.1 shows the particle densities of solids of different sizes present in flushed dairy manures of the four dairies.

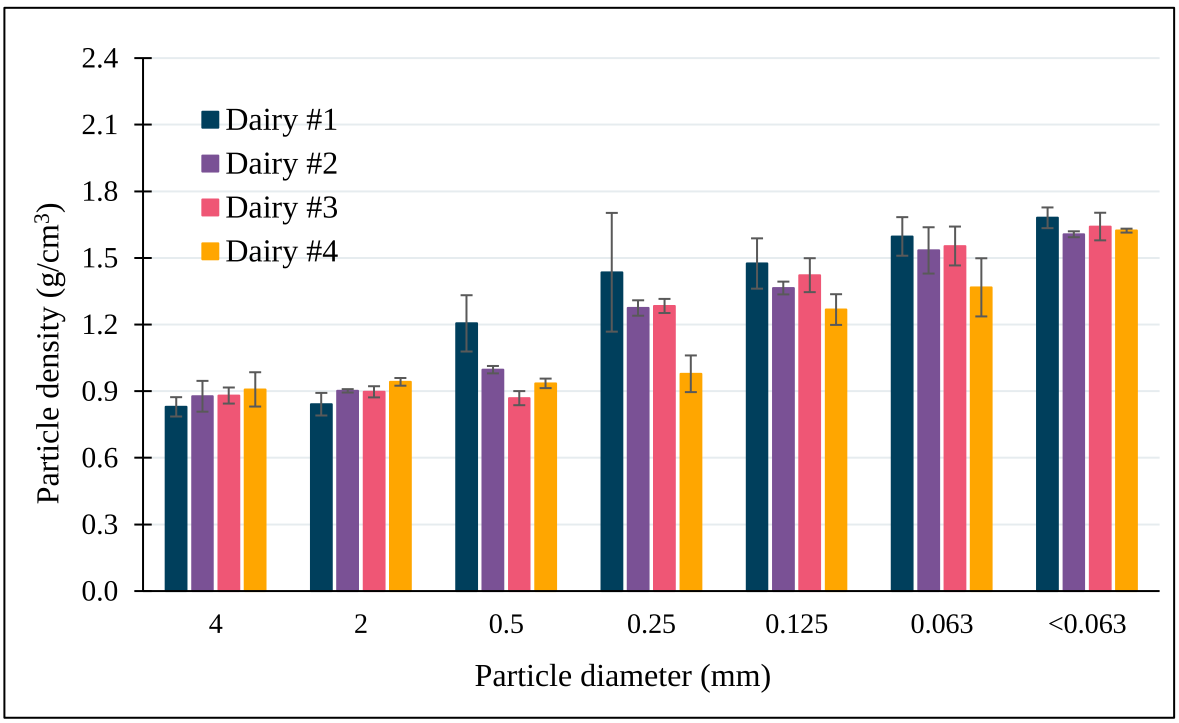

Figure 4.1: Particle density of solids present in flushed dairy manures of the four dairies. Each bar represents a mean value (n=3), and the error bars represent the associated standard deviations.

The particle densities of solids belonging to 4- and 2-mm diameter groups were not statistically significant for all four dairies. For dairies, #2, #3, and #4, 2- and 0.5-mm solids also had statistically similar particle densities, while the two diameter groups were statistically different for Dairy #1. Dairies #1 and #2 had statistically different particle densities for solids >4 mm and >0.5 mm, while the particle densities for the same were statistically similar for dairies, #3 and #4. Further, dairies, #1, #2, and #3 had statistically similar particle densities for finer solids belonging to the 0.063- and <0.063-mm diameter groups, and on contrary, Dairy #4 had statistically different particle densities for solids of 0.063- and <0.063-mm diameter groups.

Based on the weighted average of particle densities, the average particle densities for dairies #1, #2, #3, and #4 were found to be 1.49±0.01 g/cm^3, 1.36±0.01 g/cm^3, 1.37±0.02 g/cm^3, and 1.30±0.02 g/cm^3, respectively.

4.4 Particle size distribution

The particle size distributions (PSDs) of flushed manures of the four dairies are presented below. The PSD is expressed as a percentage of particle mass associated with different particle diameter groups. Figure 4.2 shows the representative solid particles retained on different sieves during the wet sieving method.

Figure 4.2: Representative sample solids retained on different sieves during the wet sieving analysis. From left to right: 4 mm, 2 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm.

4.4.1 Particle size distribution of Dairy #1

The highest percentage of solids in flushed dairy manure of Dairy #1 was found to be below 0.001-mm diameter (36.40±0.42%), followed by 0.5-mm diameter group with 11.34±0.90% TS. The third-highest percentage of TS belonged to the 4-mm diameter group with 8.98±1.18%. The 2-, 0.25-, 0.125- and 0.063-mm diameter groups had 5.08±0.47%, 3.81±0.05%, 2.83±0.44%, and 4.41±0.51% of TS, respectively. Only 16.40% of solids were present between 0.0063- and 0.001-mm diameter groups. Most of the solids in flushed dairy manure of Dairy #1 belonged to finer particle diameters. About 63.85% of solids were found to be smaller than the 0.5-mm diameter group. During the experiment, 10.74% of solids were found to be lost. The complete distribution of solids in flushed dairy manure of Dairy #1 can be found in Figure 4.3.

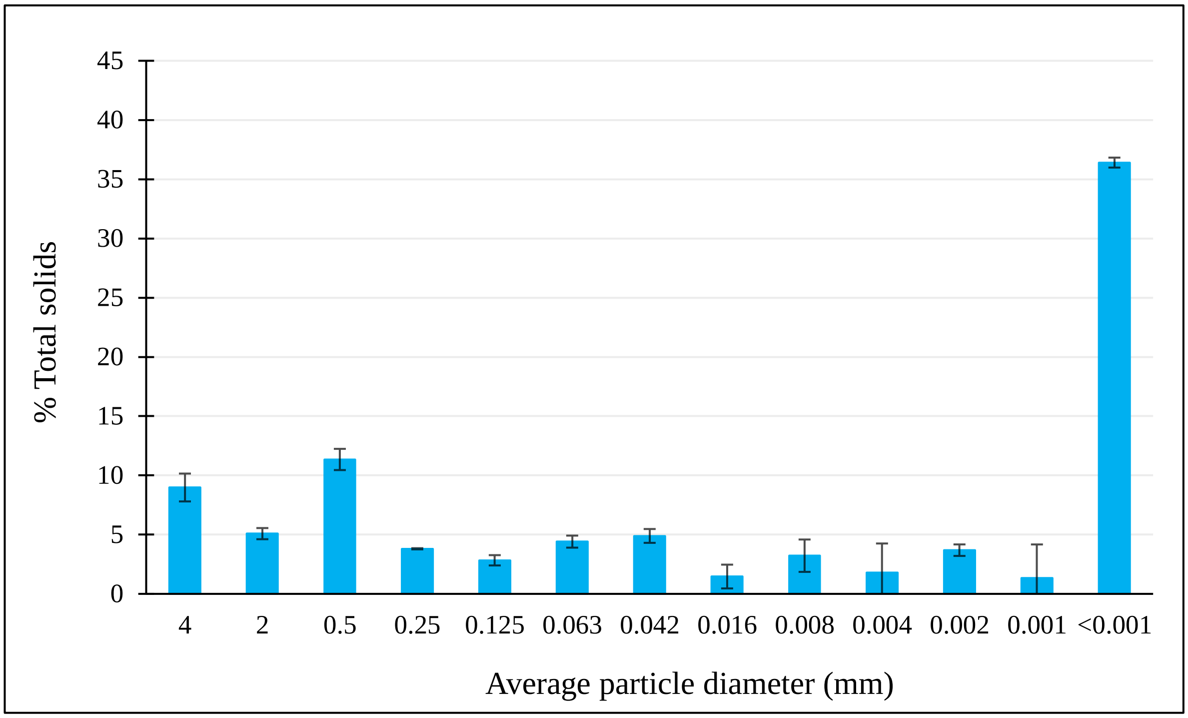

Figure 4.3: Particle size distribution of the flushed dairy manure of Dairy #1.

4.4.2 Particle size distribution of Dairy #2

For Dairy #2, the highest percent of solids belonged to <0.001-mm diameter group at 28.06±1.39%, and the second-highest percent of solids belonged to the 4-mm diameter group (14.35±0.27%) followed by 0.5-mm diameter group (10.30±0.11%). The percent of solids belonging to the 2-mm diameter group was 8.86±0.37%. Likewise, the percent of solids belonging to 0.25-, 0.125-, and 0.063-mm diameter groups were 5.43±1.15%, 4.92±0.16%, and 4.17±0.22%, respectively. The percent of solids lying between 0.063- and 0.001-mm diameter groups was 15.59%. Dairy #2 also had most of the solids in its flushed manure belonging to finer particle diameters with 58.17% of solids below 0.5 mm. About 8.31% of solids were found to be lost during the study period. The complete distribution of solids in flushed dairy manure of Dairy #2 is provided in Figure 4.4.

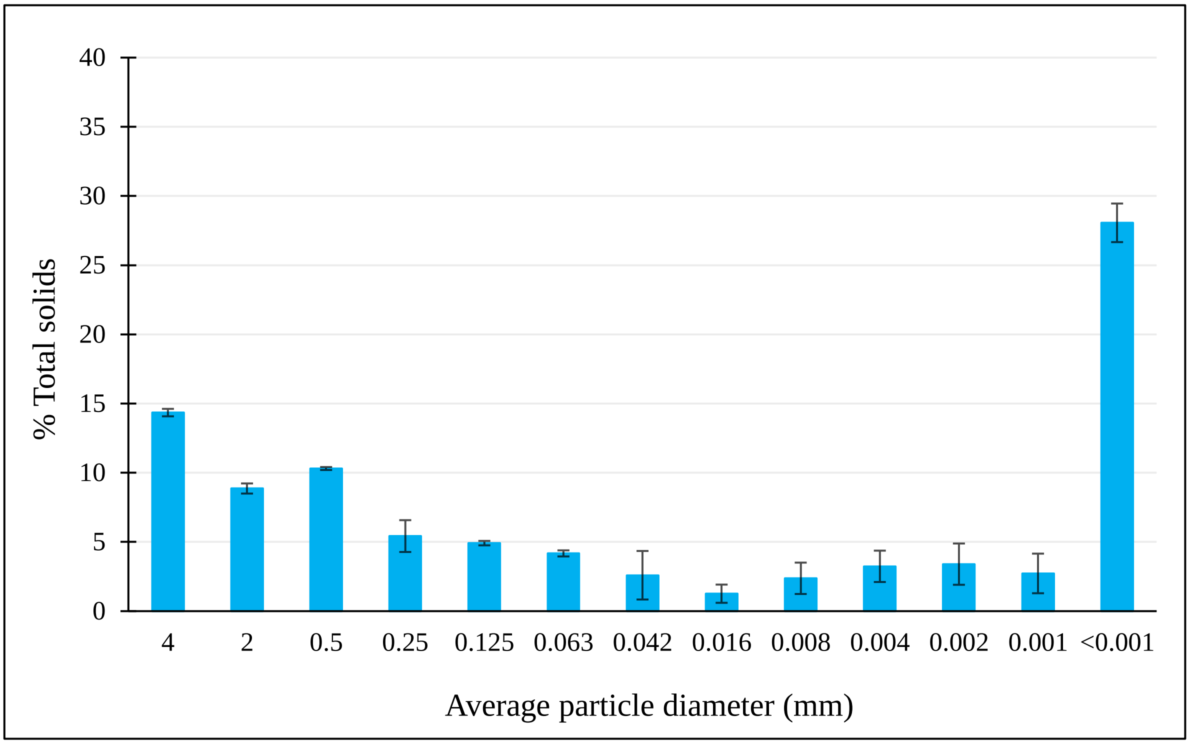

Figure 4.4: Particle size distribution of the flushed dairy manure of Dairy #2.

4.4.3 Particle size distribution of Dairy #3

For Dairy #3, the highest percent of solids belonged to the <0.001-mm diameter group (18.93±1.16%). The second-highest percent was for the 4-mm diameter group with 14.11±0.43% followed by the 0.5-mm diameter group (9.55±0.39%). The percentages of solids belonging to 2-, 0.25-, 0.125-, and 0.063-mm diameter groups were 8.21±0.68%, 3.98±0.55%, 5.22±0.57%, and 3.44±0.16%, respectively. Likewise, the percentage of solids between 0.063- and 0.001-mm was 26.37% of initial total solids. The majority of solids in flushed dairy manure of Dairy #3 also belonged to finer diameter groups with 57.94% of solids smaller than 0.5 mm. For this dairy, about 10.19% of solids were found to be lost during the experimental period.

The complete distribution of solids in flushed dairy manure of Dairy #3 can be found in Figure 4.5.

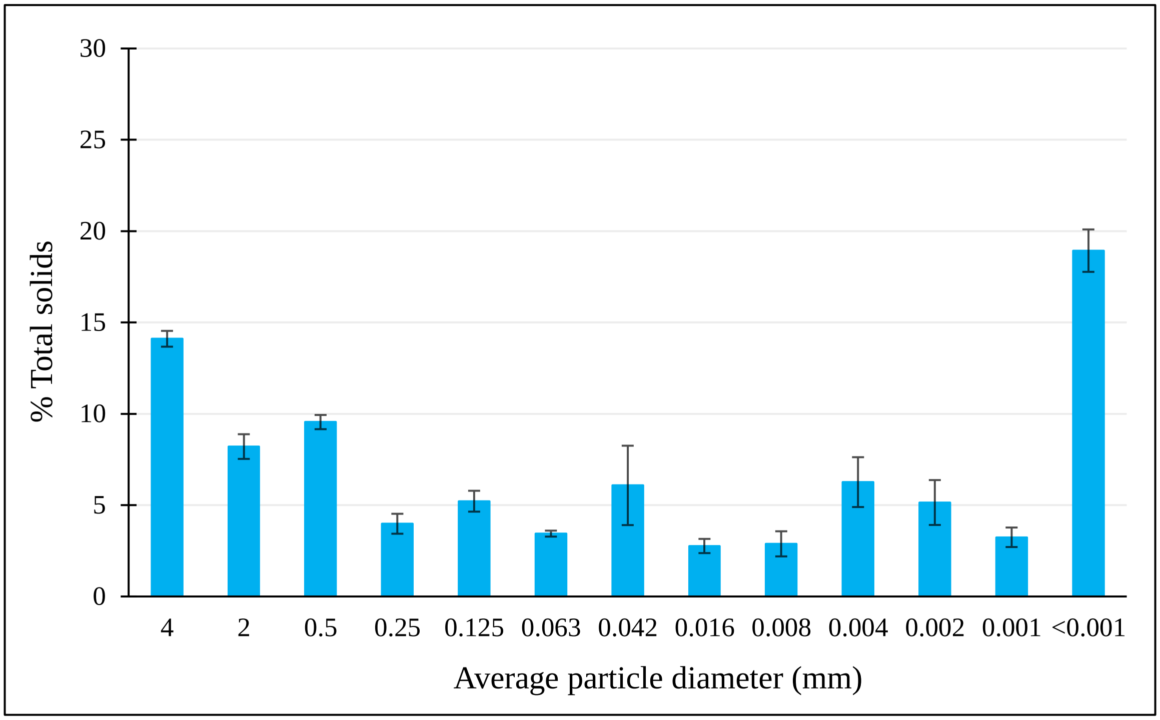

Figure 4.5: Particle size distribution of the flushed dairy manure of Dairy #3.

4.4.4 Particle size distribution of Dairy #4

Compared to the other dairies, a higher proportion of coarser particles was observed in the flushed manure of Dairy #4 as evidenced by the highest percent of solids (17.36±0.25%) belonging to the 4-mm diameter group among all the dairies. The next diameter group with the highest percent of solids was 0.041-mm with 14.09±0.8% followed by <0.001-mm with 12.88±0.80%. The percentages of solids belonging to 2-, 0.5-, 0.25-, 0.125-, and 0.063-mm were 10.55±0.24%, 9.49±0.23%, 4.95±0.18%, 4.67±0.26%, and 4.04±0.06%, respectively. The particle diameter group 0.0042-mm had a considerably larger value (14.09±0.8%)

compared to the other dairies. The percentage of solids between 0.063- and 0.001-mm diameter groups was found to be 24.95%. Although the dairy had a higher proportion of coarser solids, the majority of solids were still smaller than 0.5 mm (51.50%). For this dairy, about 11.10% of solids were found to be lost during the study period. The complete distribution of solids in flushed dairy manure of Dairy #4 is presented in Figure 4.6.

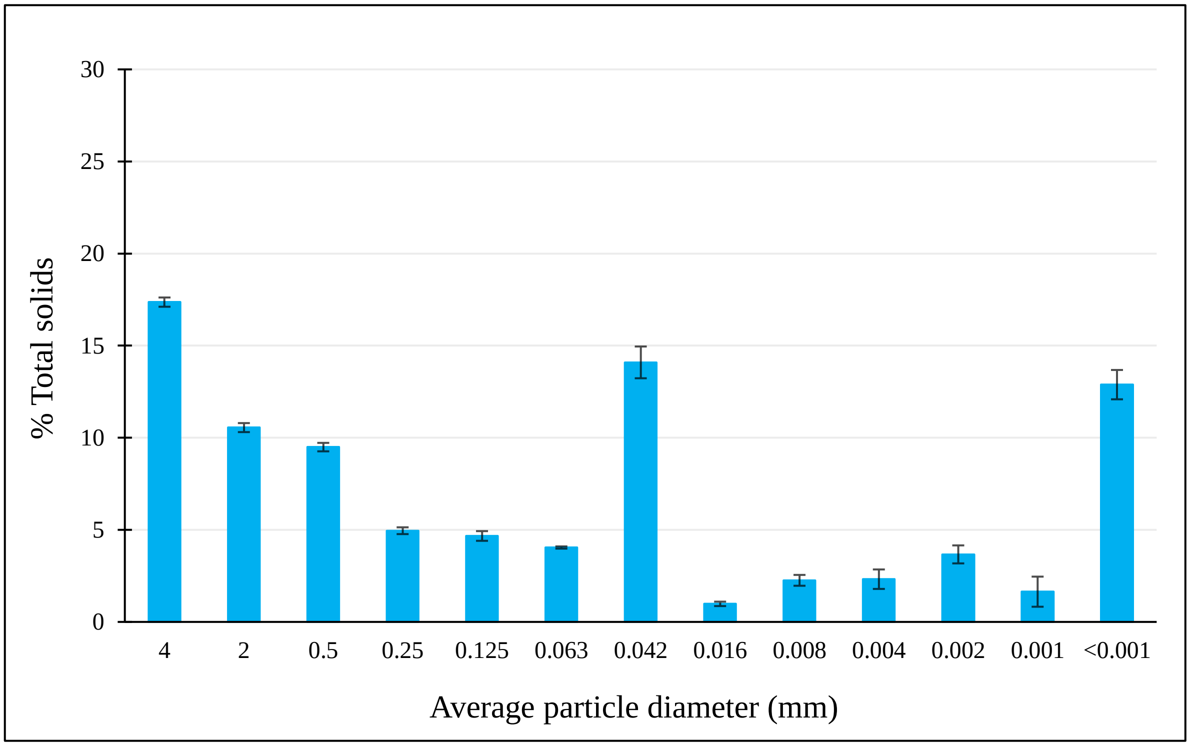

Figure 4.6: Particle size distribution of the flushed dairy manure of Dairy #4.

4.5 Cumulative particle size distribution (Cumulative percent solids retained)

The cumulative particle size distributions of the flushed dairy manures of the four dairies are given in Table 4.3 and Figure 4.7. Statistical analyses were performed on the differences between the cumulative percent of solids that would be retained/removed by different diameter groups for each dairy separately.

For Dairy #1, pore sizes, 4-, 2-, and 0.5-mm would remove a statistically significant quantity of solids (8.99%, 14.06%, and 25.4%) from the flushed dairy manure. However, the solids that would be removed by screen pore sizes of 0.5- and 0.25-mm (25.4% and 29.21%) were not statistically different. The percentages of solids that would be removed by pore sizes, 0.25- and 0.125-mm were statistically similar, while the 0.5- and 0.125-mm pore sizes were statistically different for the percent of total solids that would be removed from flushed dairy manure.

For Dairy #2, the screen pore sizes, 4-, 2-, 0.5-, 0.25-, 0.125-, and 0.063-mm would remove statistically different percent of solids from the flushed dairy manure—14.37%, 23.22%, 33.53%, 38.95%, 43.87%, and 48.03%, respectively.

For Dairy #3, all the screen pore sizes would remove a significantly different percentage of solids from flushed dairy manure outside of 0.016-mm pore size which was statistically similar with both 0.042- and 0.008-mm pore sizes for TS removal.

Finally, the percentages of solids that would be removed from flushed dairy manure of Dairy #4 by particle diameters from 4 mm to 0.001 mm were statistically different except for 0.016-mm pore size which had a statistically similar TS removal percentage with the 0.042-mm diameter group.

Table 4.3: Cumulative particle size distributions in flushed dairy manures of the four dairies.

Diameter (mm)	Cumulative %TS			
	Dairy #1	Dairy #2	Dairy #3	Dairy #4
4	8.98±1.18a	14.35±0.27a	14.11±0.43a	17.36±0.25a
2	14.06±1.54b	23.21±0.48b	22.32±1.00b	27.91±0.39b
0.5	25.41±2.29c	33.52±0.56c	31.86±0.66c	37.40±0.61c
0.25	29.21±2.34cd	38.95±0.75d	35.84±1.19d	42.36±0.67d
0.125	32.04±1.95de	43.86±0.88e	41.06±1.03e	47.02±0.93e
0.063	36.46±2.44ef	48.03±0.80f	44.50±0.88f	51.06±0.95f
0.042	41.34±2.29fg	50.63±2.54fg	50.58±2.33g	65.15±0.38g
0.016	42.81±3.50gh	51.89±2.66gh	53.35±2.41gh	66.13±0.35g
0.008	46.03±1.41gh	54.26±1.83h	56.23±1.83h	68.39±0.56h
0.004	47.82±1.06hi	57.50±0.75i	62.49±0.53i	70.71±0.38i
0.002	51.50±2.44i	60.90±1.04j	67.63±1.71j	74.38±0.29j
0.001	52.85±2.30i	63.63±0.49j	70.87±1.23k	76.02±0.98k

Note: Means (n=3) ± standard deviations within each dairy (column) followed by different letters are statistically different from each other ($p<0.05$).

The cumulative particle size distribution of the flushed manure varied between the four dairies and was found to be site-specific. The solid distribution patterns for Dairy #2 and Dairy

#3 with similar initial TS content (4.97% and 4.42% for dairies #2 and #3, respectively) were more closely aligned with each other compared to the other dairies. Figure 4.7 is the graphical representation of the cumulative grain size distributions of the flushed dairy manures of the four dairies.

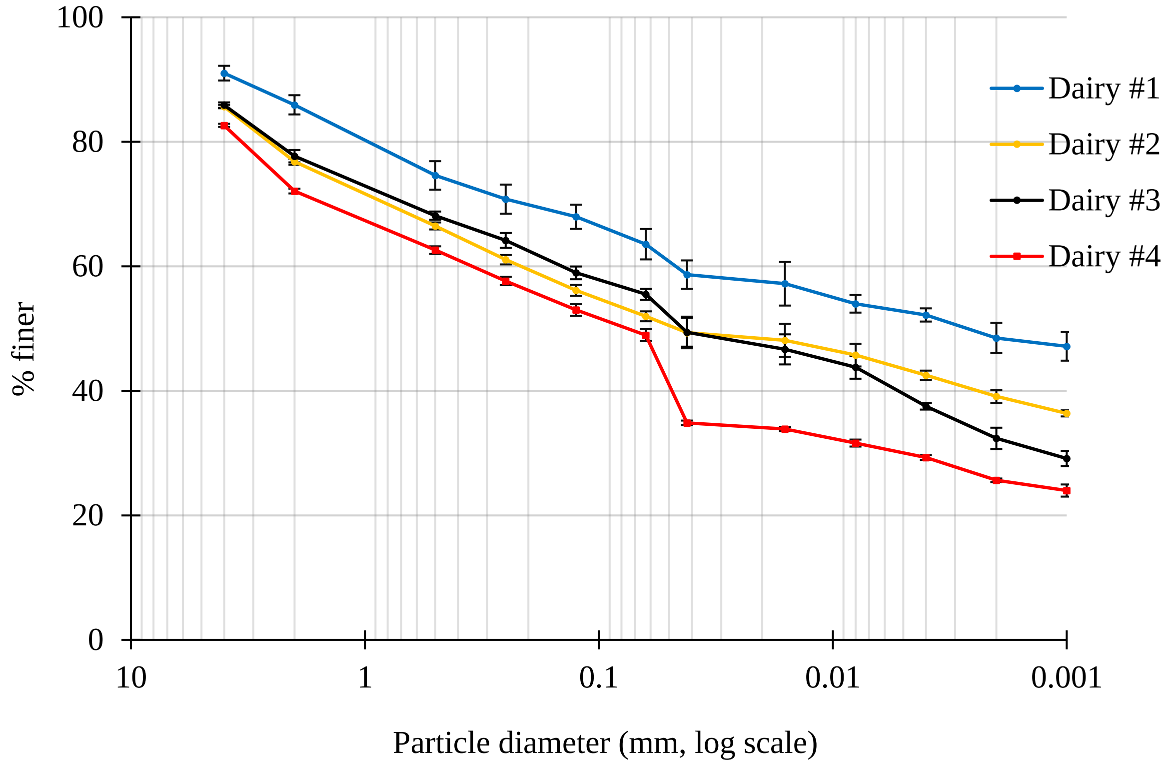

Figure 4.7: Plot of percent finer vs particle diameter for the four dairies.

4.6 Nutrient distribution

4.6.1 Total nitrogen and total phosphorous distribution of Dairy #1

The total nitrogen (TN) and total phosphorous (TP) distributions of the flushed dairy manure of Dairy #1 are given in Figure 4.8. Compared to TS content, the three samples exhibited considerable variations in TN and TP contents as evidenced by large standard deviations in Figure 4.8.

The diameter group <0.001-mm consisted of the highest percentage of TN at 47.20±5.17%. The diameter group that had the second-highest percent of TN was 2-mm with 14.41±7.11% TN, followed by the 4-mm diameter group with 11.06±2.84%. The diameter groups 0.5-, 0.25-, 0.125-, and 0.063-mm had 2.86±2.62%, 4.66±2.32%, 2.53±0.96%, and 2.17±1.60% of total nitrogen, respectively. About 15.88% of TN belonged to particles with diameters between 0.063- and <0.001-mm. Most of the total nitrogen was found to be associated with finer particles. The dairy had 75.50% TN associated with solids below 0.5-mm diameters and 68.30% below 0.125-mm diameter groups.

The distribution of TP was similar to the distribution of TN in that most TP was associated with finer particles. The diameter group <0.001-mm had the highest percent of TP with 44.06±1.77% followed by the 0.016-mm diameter group with 7.70±0.94%. The diameter groups 0.008-mm and 0.5-mm had similar percentages of TP belonging to the 0.016-mm diameter group with 7.58±0.50% and 7.39±1.02%, respectively. The diameter groups 4-, 2-, 0.25-, 0.125-, and 0.063-mm had about 3.66±4.55%, 3.30±2.15%, 4.11±1.77%, 3.83±1.44%, and 2.26±0.14% of TP, respectively. The percentage of TP lying between 0.063- and <0.001-

mm diameter groups was 31.39%. The dairy had 85.6% of TN associate with solids having diameters below 0.5-mm and 77.71% associated with solids below 0.125-mm diameter groups.

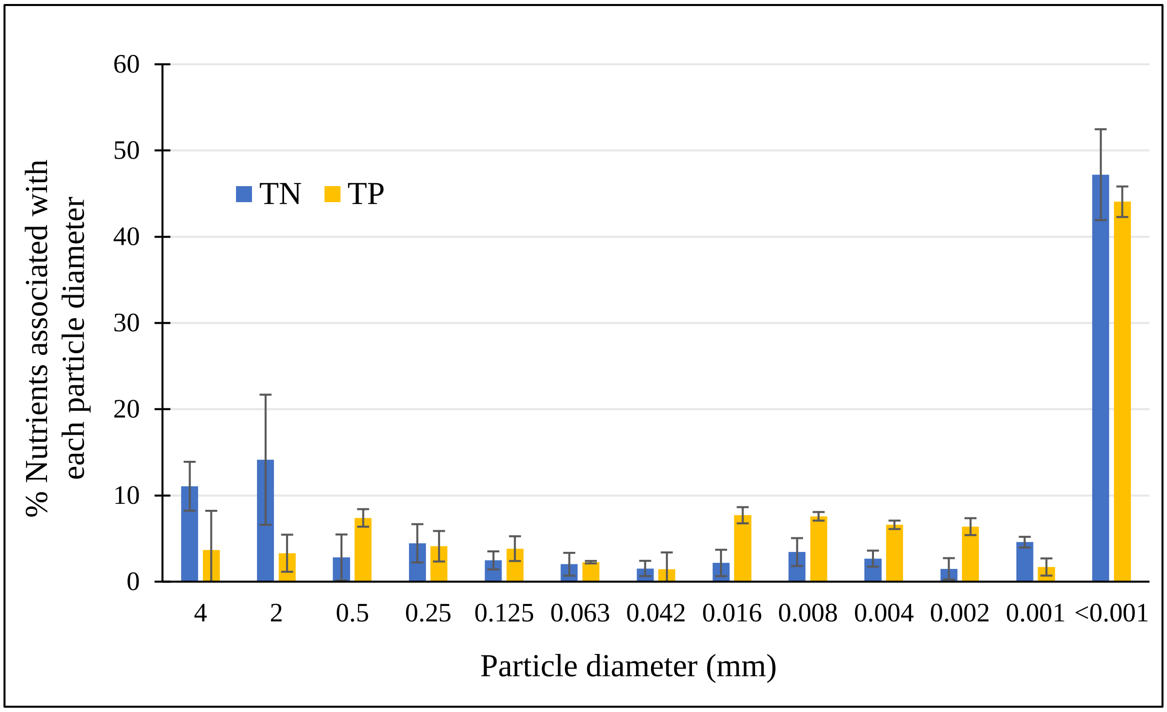

Figure 4.8: Distribution of total nitrogen and total phosphorous in the flushed dairy manure of Dairy #1.

4.6.2 Total nitrogen and total phosphorous distribution of Dairy #2

The distributions of TN and TP in the flushed dairy manure of Dairy #2 are presented in Figure 4.9.

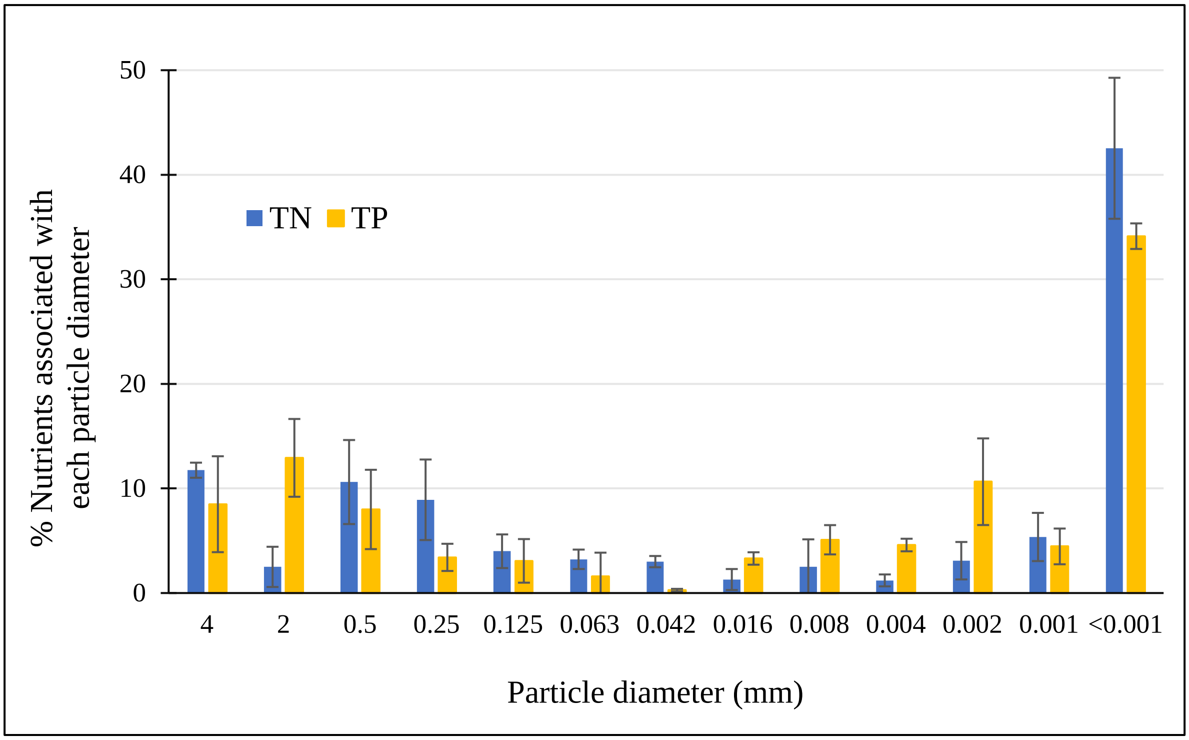

Figure 4.9: Distribution of total nitrogen and total phosphorous in the flushed dairy manure of Dairy #2.

Dairy #2 also had considerable variations in the nutrient contents among the three samples taken for the study. The highest percent of TN was found to be associated with solids belonging to the <0.001-mm diameter group with 42.53±6.74% followed by solids associated with the 4-mm diameter group with 11.75±0.72%. The next highest %TN was associated with the 0.5-mm diameter group at 10.61±4.02%. Likewise, diameter groups 2-, 0.25-, 0.125-, and 0.063-mm had 2.50±1.92%, 8.92%±3.85%, 4.00±1.61%, and 3.23±0.93% of TN, respectively. The percentage of TN between 0.063- and <0.001-mm diameter groups was 16.46%. The percent of TN belonging to solids of diameter groups below 0.5-mm was 75.14%, while that belonging to solids <0.125-mm diameter group was 62.22%.

Regarding TP, the diameter group with the highest percent of TP was <0.001-mm at 34.13±1.22%. The second and third highest percentages of TP were found to be associated with 2- and 0.002-mm particle diameter groups at 12.93±3.72% and 10.65±4.14%, respectively. The 4-mm diameter group had the next highest TP content with 8.50±4.59% followed by the 0.5-mm diameter group with 7.99±3.79%. The diameter groups 0.25-, 0.125-, and 0.063-mm had about 3.41±1.30%, 3.08±2.08%, and 1.58±2.28% of TP, respectively. The percentage of TP between 0.063- and <0.001-mm diameter groups was 28.39%. Likewise, the percentages of TP belonging to particle diameters <0.5-mm and <0.125-mm groups were 70.58% and 64.09%, respectively.

4.6.3 Total nitrogen and total phosphorous distribution of Dairy #3

The distributions of TN and TP in the flushed dairy manure of Dairy #3 are given in Figure 4.10. It can be seen in the figure that Dairy #3 also had high variations in nutrient contents between the three samples as evidenced by large standard deviations.

The <0.001-mm diameter group consisted of the highest percentage of TN at 48.98±5.48%. The 4-mm diameter group had the second-highest percentage of TN (11.33±3.16%), closely followed by 0.5-mm diameter groups with 10.47±5.68%. The diameter groups, 2-, 0.25-, 0.125-, and 0.063-mm had 2.44±0.89%, 4.49±3.43%, 5.01±1.01%, and 1.67±1.29% of TN, respectively. About 15.61% of TN was found to be linked with particles having diameters between 0.063- and <0.001-mm. The percentages of TN associated with finer diameters, <0.5- and <0.125-mm were 75.76% and 66.26%, respectively.

Like TN, most of the TP in flushed dairy manure of Dairy #3 was associated with finer particles with 69.28% and 61.15% TP belonging to <0.5- and <0.125-mm diameter groups, respectively. The diameter group <0.001 mm had the highest percentage of TP (36.53±0.32%) followed by the 4-mm diameter group with 14.67±2.39% TP. The 0.5-mm diameter group had the next highest percentage of TP with 9.86±1.43%. The percentages of TP belonging to 2-, 0.25-, 0.125-, and 0.063-mm diameter groups were 6.19±1.46%, 1.73±1.01%. 6.39±0.61%, and 2.45±1.08%, respectively. Similarly, the percentage of TP belonging to particle diameter between 0.063- and <0.001-mm was 22.17%.

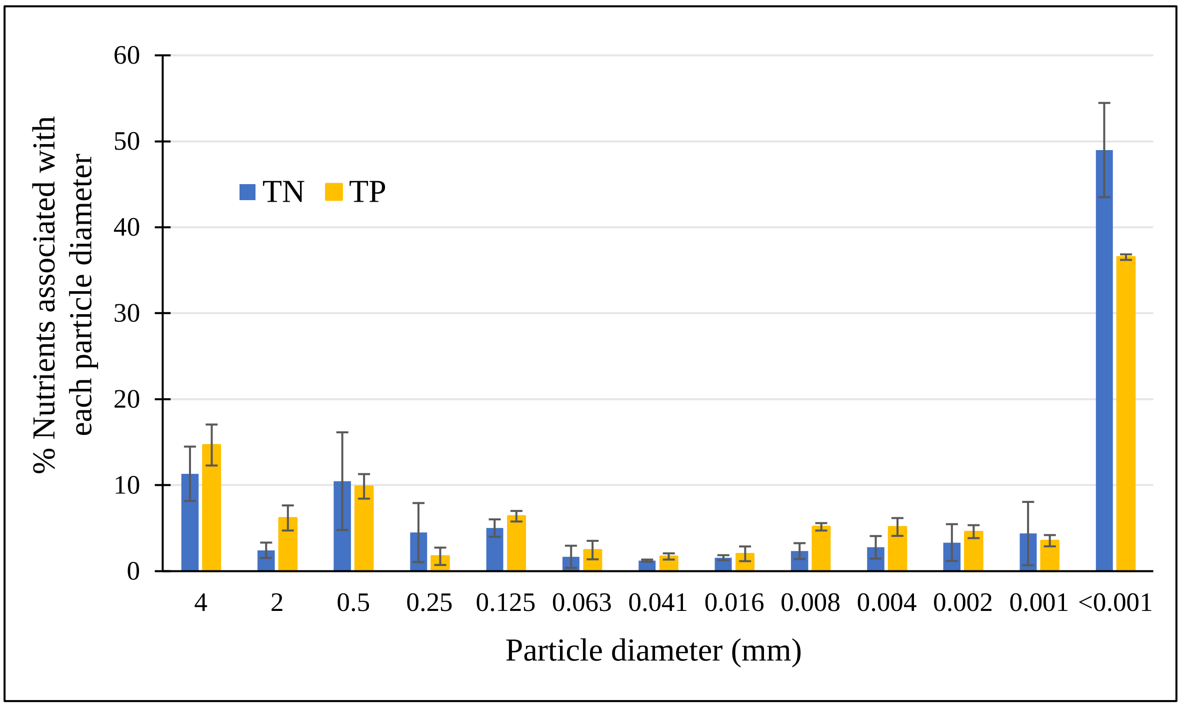

Figure 4.10: Distribution of total nitrogen and total phosphorous in the flushed dairy manure of Dairy #3.

4.6.4 Total nitrogen and total phosphorous distribution of Dairy #4

Dairy #4 had a characteristically lower amount of nutrients between 0.0063- and <0.001-mm diameter groups. Most nutrients were either associated with >0.063-mm or

<0.001-mm diameter groups. The dairy had similar TN and TP distribution patterns as seen in Figure 4.11. The highest percentages of TN and TP were found to be associated with <0.001-mm diameter group at 35.49±0.63% TN and 32.75±1.12% TP. The diameter group with the second-highest percentage of nutrients was 4-mm with 17.77±1.07% TN and 19.61±0.79% TP. Regarding nutrients below <0.5- and <0.125-mm diameter groups, the dairy had about 61.92% and 48.02% of TN and 61.35% and 44.96% of TP, respectively. The complete distributions of TN and TP in the flushed dairy manure of Dairy #4 can be found in Figure 4.11.

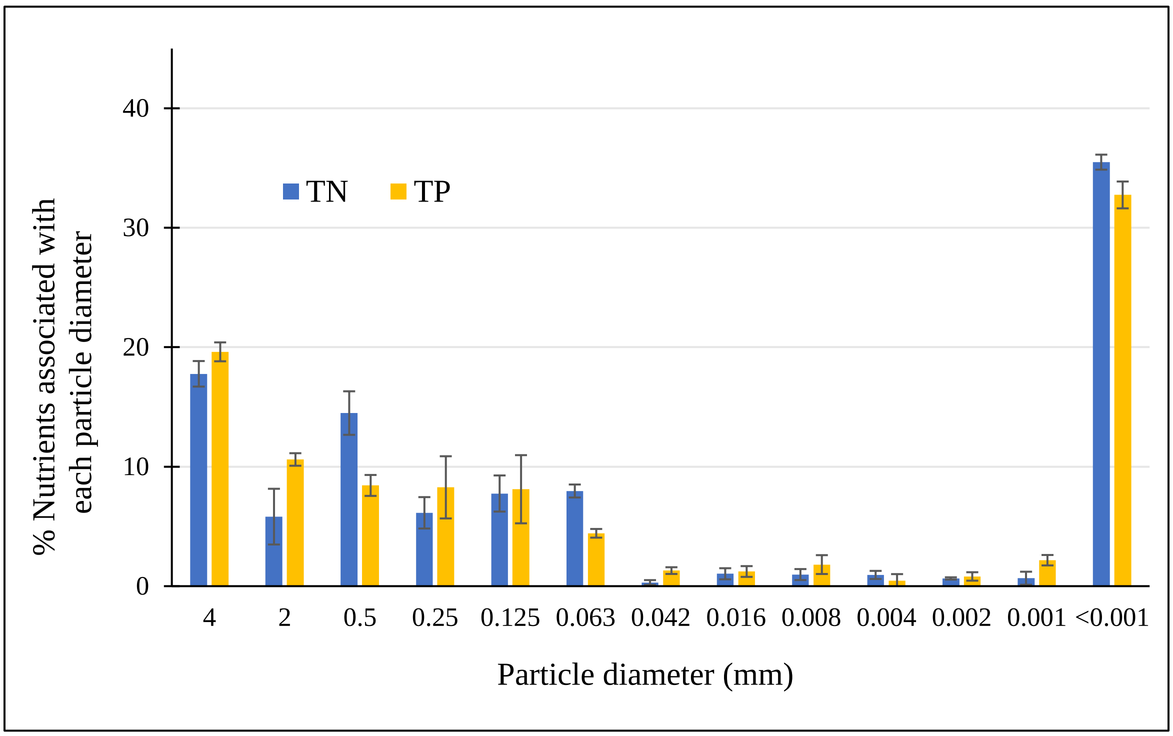

Figure 4.11: Distribution of total nitrogen and total phosphorous in the flushed dairy manure of Dairy #4.

4.7 Cumulative nutrient distribution (Cumulative percent nutrients retained)

4.7.1 Cumulative total nitrogen distribution

The cumulative percent of total nitrogen (TN) in flushed dairy manures of the four dairies associated with solids of different diameter groups and the statistical significances of different diameter groups (equivalent to different pore sizes of inclined screen separators) for TN removal are presented in Table 4.4.

Table 4.4: Cumulative total nitrogen distributions of flushed dairy manures of the four dairies.

Diameter (mm)	Cumulative %TN			
	Dairy #1	Dairy #2	Dairy #3	Dairy #4
4	11.06±2.84a	11.75±0.72a	11.33±3.16a	17.77±1.07a
2	25.21±4.71b	14.25±2.64a	13.76±3.61a	23.59±2.75b
0.5	28.00±6.97bc	24.86±3.55b	24.24±7.39b	38.08±0.94c
0.25	32.45±5.58bcd	33.78±1.17c	28.72±5.02bc	44.22±1.36d
0.125	34.91±6.14bcde	37.78±2.75cd	33.74±4.18cd	51.98±1.20e
0.063	36.93±4.84cdef	41.01±2.56cde	35.41±3.19cd	59.94±1.01f
0.042	38.46±5.00cdef	44.01±3.09def	36.64±3.07cde	60.25±0.88fg
0.016	40.63±5.35def	45.30±4.06def	38.20±3.07cde	61.29±0.90fgh
0.008	44.06±4.46defg	47.81±6.68efg	40.54±2.67de	62.26±1.34fghi
0.004	46.73±5.01efg	49.02±7.21efg	43.31±2.36def	63.20±1.01ghi
0.002	48.22±5.88fg	52.11±5.42fg	46.64±3.79ef	63.84±1.01hi
0.001	52.80±5.27g	57.47±6.74g	51.02±5.48f	64.51±0.63i

Note: Means (n=3) ± standard deviations within each dairy (column) followed by different letters are statistically different from each other ($p<0.05$).

The statistical significances of TN removal capacities of different pore-sized inclined screen separators from the flushed dairy manures were found to be dairy-specific.

For Dairy #1, a 4-mm pore-sized solid-liquid separator would remove 11.06% of TN, statistically significantly lower than the percent of TN that would be removed by a 2-mm pore-sized separator (25.21%). However, the percentages of TN that would be removed by 2-, 0.5-, 0.25-, and 0.125-mm pore-sized separators (25.21%, 28.00%, 32.45%, and 34.91%) were found to be statistically similar. A 0.063-mm pore-sized separator would remove a statistically different percent of TN (36.93%) from a 2-mm pore-sized separator, but the 0.063-mm pore-sized separator would remove statistically similar percent of TN from 0.5-, 0.25-, 0.125-, and 0.041-mm pore-sized separators.

In the case of Dairy #2, the 4- and 2-mm pore-sized solid-liquid separators would remove a statistically similar percent of TN with 11.75% and 14.25%, respectively. A 0.5-mm pore-sized separator would remove a significantly higher percent of TN (24.86%) from 2-mm pore-sized separator. Likewise, a 0.25-mm pore-sized separator would remove a statistically higher percentage of TN (33.78%) than a 0.5-mm pore-sized separator. However, 0.25-, 0.125-, and 0.063-mm pore-sized separators would remove statistically similar percentages of TN from the flushed dairy manure of Dairy #2.

Regarding Dairy #3, 4- and 2-mm pore-sized screen separators would remove statistically similar percentages of TN (11.33% and 13.76%, respectively). However, the percent of TN that would be removed by a 0.5-mm screen separator (24.24%) was found to be statistically different from a 2-mm pore-sized separator. On the other hand, a 0.25-mm pore-sized would remove a statistically similar percent of TN (28.72%) as a 0.5-mm pore-sized separator.

For Dairy #4, the pore sizes 4-, 2-, 0.5-, 0.25-0.125- and 0.063-mm would remove statistically different percentages of TN—17.77%, 23.59%, 38.08%, 44.22%, 51.98%, and 59.94%—from the flushed dairy manure.

4.7.2 Cumulative total phosphorous distribution

The cumulative percent of total phosphorous (TP) that could be removed by different pore-sized inclined screen separators from the flushed dairy manures of the four dairies and the statistical significances between the TP removal capacities of those pore sizes are presented in Table 4.5.

Table 4.5: Cumulative total phosphorous distributions of flushed dairy manures of the four dairies.

Diameter (mm)	Cumulative %TP			
	Dairy #1	Dairy #2	Dairy #3	Dairy #4
4	3.66±4.55a	8.50±4.59a	14.67±2.39a	19.61±0.79a
2	6.96±4.02a	21.42±1.39b	20.86±1.24b	30.22±0.40b
0.5	14.36±3.10b	29.42±5.19c	30.72±1.12c	38.65±0.52c
0.25	18.46±2.85bc	32.83±4.01cd	32.45±1.98c	46.92±2.08d
0.125	22.29±3.59bc	35.91±4.43cde	38.85±1.38d	55.04±0.77e
0.063	24.55±3.70cd	37.49±2.27de	41.30±0.33de	59.46±0.58f
0.042	26.00±1.95cd	37.77±2.16de	43.01±0.64ef	60.76±0.54fg
0.016	33.70±1.01de	41.08±2.73ef	45.03±0.66f	61.99±0.29gh
0.008	41.27±0.69ef	46.17±1.52fg	50.19±0.51g	63.80±0.99hi
0.004	47.86±1.16fg	50.77±1.93g	55.33±0.93h	64.27±0.46i
0.002	54.24±1.65g	61.41±2.23h	59.93±0.34i	65.08±0.81i
0.001	55.94±1.77g	65.87±1.22h	63.47±0.32j	67.25±1.12j

Note: Means (n=3) ± standard deviations within each dairy (column) followed by different letters are statistically different from each other ($p<0.05$).

The statistical significances of TP removal capacities of different pore-sized inclined screen separators were also found to be dairy-specific.

For Dairy #1, 4- and 2-mm pore sizes would remove/retain statistically similar percentages of TP (3.66% and 6.96%) from the flushed dairy manure. A 0.5-mm pore-sized separator would remove 14.36% of TP, statistically different from the percent of TP that would be removed by 2- and 4-mm pore-sized separators. It was found that 0.5-, 0.25-, and 0.125-mm pore-sized separators would remove a statistically similar percent of TP (14.36%, 18.46%, and 22.29%). However, the percentages of TP that would be removed by 0.5- and 0.063-mm pore-sized separators were found to be statistically different.

In the case of Dairy #2, 4-, 2-, and 0.5-mm pore-sized separators would remove 8.50%, 21.42%, and 29.42% of TP from the flushed dairy manure, statistically different from one another. However, the percentages of TP that would be removed by 0.5-, 0.25-, and 0.125-mm (29.42%, 32.83%, and 35.91%) were found to be statistically similar.

The percentages of TP that would be removed from the flushed dairy manure of Dairy #3 by 4-, 2-, and 0.5-mm pore-sized separators were found to be statistically different (14.67%, 20.86%, and 30.72%). However, 0.5- and 0.25-mm pore-sized separators would remove statistically similar percentages of TP (30.72% and 32.45%). Also, the percentage of TP that would be removed by a 0.125-mm pore-sized separator was found to be statistically different from the percent of TP that would be removed by 0.25-mm pore-sized separators.

A comparatively higher percentage of TP in the flushed dairy manure of Dairy #4 was found to be associated with larger particles. It was found that the 4-, 2-, 0.5-, 0.25-, 0.125-, and 0.063-mm pore sized separators would remove statistically different percentages of TP

(19.61%, 30.22%, 38.65%, 46.92%, 55.04%, and 59.46%) from the flushed dairy manure of Dairy #4.

Chapter 5: Discussions, summary, conclusions, limitations, and recommendations for future research

This chapter begins by discussing the findings of the study. Under discussion, the four dairy farms are compared for the study parameters. It also compares the results of this study with the studies from the past and identifies the areas of similarities and differences and provides a possible explanation for the similarity or disparity. It then summarizes the study before providing the concluding remarks. The limitations and major implications of the study are then presented. The chapter concludes by providing suggestions and recommendations for future research.

5.1 Discussions of findings

5.1.1 Initial total solid content

Meyer et al. (2007) argued that variation in total solids (TS) content could arise from the differences in feedstuff particle size and digestibility of animals, while Chastain et al. (2001) linked the variation in total solids content to the difference in amounts of bedding and wasted feed mixed with the manure. Zhang & Westerman (1997) also posited that feed rations, animal species, growth stages of animals, manure collection methods, and the amount of water added into the manure collection systems largely affect manure characteristics.

In Dairy #1, cows were mostly out in open, and flushing was done only in the feeding area. The lesser time spent by dairy cows in the flushing zone could have resulted in the lower amounts of bedding materials and feedstuffs mixed with the flushed dairy manure. Also, lesser time spent means a low amount of manure produced in the flushing zone, and as a result a more diluted flushed manure. These factors could have resulted in the lowest initial TS content in flushed dairy manure of Dairy #1. In the freestall barns that were used by the other three dairies, cows were free to move around all the time inside the barns, which presented a greater chance of mixing of bedding materials and spilled feedstuffs with manure. This could have contributed to the higher initial TS contents of flushed dairy manures of dairies, #2, #3, and #4 compared to Dairy #1. Dairy #4 also had an anaerobic digestion facility. A higher number of dairy cows and a conscious effort by the dairy farmer of Dairy #4 to maintain a higher amount of solids in flushed dairy manure for the anaerobic digestion process could be some reasons for the highest initial TS content observed on its flushed dairy manure.

Regardless, the initial total solids contents in the flushed dairy manures of the four dairies in this study were found to be similar to the TS of flushed dairy manures of different dairies reported in the literature: 3.83%, 7.7%, 6.7%, 0.52–2.95%, and 0.38–4.83% reported by Chastain et al. (2001), Christensen & Sommer (2013), Ford & Fleming (2002), Hegg et al. (1981), and Meyer et al. (2004), respectively.

5.1.2 Initial total nitrogen and total phosphorous content

The initial total nitrogen (TN) and total phosphorous (TP) contents in the flushed dairy manures of the four dairies were found to be similar to the studies reported in the literature; Chastain et al. (2001), Christensen & Sommer (2013), and Ford & Fleming (2002) reported TN of 0.14%, 0.32%, and 0.29% and TP of 0.09%, 0.085%, and 0.08%, respectively.

Like TS, the variation in the nutrient content among the four dairies can be attributed to the differences in dairy management practices and digestive performances of cows between the four dairies. Van Horn (1998) and Wright (2005) attributed the variations in TN content with particle size to the difference in organic nitrogen content in feed and the digestibility of animals. Hjorth et al. (2011) and Zhang (2002) argued that the mixing of bedding materials and spilled feed and the extent of dilution also impact nutrient composition and distribution in manure. High dilution in the case of Dairy #1 and low dilution for Dairy #4 could be the major reason for the lowest and the highest nutrient (TN and TP) contents in flushed dairy manures of dairies, #1 and #4, respectively.

5.1.3 Particle density

According to Lam et al. (2007) and Day & Panda (1966), dry wheat straw and dry chopped hay particles have lower particle densities—0.93–1.18 g/cm^3 and 0.85 g/cm^3, respectively. During this study, the larger solids (>0.5 mm)—predominantly hay and straw (Figure 4.2)—also had lower particle densities (0.87–1.00 g/cm^3). The higher proportion of larger solids >0.5 mm in Dairy #4 compared to the other dairies (Table 4.3) might have contributed to its lowest average particle density value among the four dairy farms. Likewise, Dairy #1 had the lowest proportion of larger solids >0.5 mm in flushed manure, and therefore, the largest particle density value. The variation in the particle density might also be due to the difference in the mineral contents of manure (Hafez et al., 1974 as reported in Sutitarnnontr et al., 2014).

The weighted average particle density of flushed dairy manures of the four dairies in this study ranged from 1.30 to 1.49 g/cm^3. Sobel (1966) as reported in Achkari–Begdouri and Goodrich (1992), Hafez et al. (1974) as reported in Sutitarnnontr et al. (2014), Bohnhoff & Converse (1987), Achkari–Begdouri & Goodrich (1992), and Sutitarnnontr et al. (2014) had reported the particle density of fresh dairy manure to be in the range of 1.24–1.60 g/cm^3, 1.43–

1.44 g/cm^3, 1.53–1.63 g/cm^3, 1.42–1.90, and 1.41–1.84 g/cm^3, respectively. The values of the particle density of flushed dairy manure obtained in this study lied toward the lower end of the spectrum of the reported particle density range for fresh dairy manure which could be due to the addition of fibrous bedding materials and wasted feedstuffs with the manure.

Compared to the commonly used particle density of soils of 2.65 g/cm^3 (Blake, 2008), the average particle density of flushed dairy manure solids was found to be much lower (1.30 to 1.49 g/cm^3). The average particle density of solids larger than 0.5 mm for the four dairies in this study ranged from 0.87 to 1 g/cm^3, and such solids constituted between 25.41% to 37.40% of total solids. This suggests that between 25.41% to 37.40% of solids never settle down in settling basins. Similarly, 24.24–38.08% of TN and 14.36–38.65% of TP associated with solids larger than 0.5 mm for the four dairies would not be removed by settling tanks.

On the other hand, the average particle density of solids smaller than 0.5 mm for the four dairies ranged from 1.24 to 1.64 g/cm^3, which suggests that the screens of 0.5 mm pore size would remove all solids that are less dense than water, and almost all solids in the separated liquid fraction would have particle densities larger than that of water. Therefore, combining the screen separation as primary treatment and settling basins as the secondary treatment could be a more effective strategy for those dairies that only have settling basins or sedimentation tanks as the primary method of solid-liquid separation.

From this study, it was observed that the settling basins would theoretically remove all solids and nutrients associated with them after the flushed dairy manure has undergone screen separation through a 0.5 mm pore-sized screen. However, due to the high viscosity of liquid manure—0.00409 Nsec/m^2 for liquid manure with 1% TS, which is about five times the viscosity of water (Sievers, 1989)—the solids in flushed dairy manure would take a long time to settle depending upon the viscosities of liquid manures and particle sizes and densities of those solids. Therefore, more advanced solid-liquid separation technologies such as centrifugation, filtration, or even membrane separation processes like micro-, ultra-, and nano-filtration or reverse osmosis could be the better options in terms of solid and nutrient removal capacities as they have been reported to remove a higher percentage of solids and nutrients from liquid dairy manure (Chastain, 2019; Ford & Fleming, 2002).

5.1.4 Particle size distribution

The particle size distribution of flushed dairy manure was found to be dairy-specific which is in accordance with the assertion of García–Mesa et al. (2010), who had argued that the particles present in the effluent of biological processes are specific to each treatment plant. Meyer et al. (2007) linked the variation in TS distribution in fresh dairy manures to the difference in feedstuff particle size and digestibility of animals. Therefore, the variation in particle size distribution across the four dairies can be attributed to the differences in management practices and digestive performances of cows.

The dairies with freestall systems (dairies, #2, #3, and #4) had higher quantities of coarser solids (33.52%, 31.86%, and 37.40% >0.5 mm for dairies, #2, #3, and #4, respectively) compared to Dairy #1 (25.41% >0.5 mm) with an open lot system, which can be expected because of a greater chance of mixing of bedding materials with manure as cows are continuously moving in and out of their stalls.

The highest percent of solids larger than 0.5 mm in the flushed dairy manure of Dairy #4 indicates that a higher amount of bedding material and undigested feedstuffs were mixed with its flushed manure. Dairy #4 also had a considerably higher percentage of TS belonging to the 0.042 mm diameter group compared to the other three dairies. The higher solids observed could have been due to the presence of a larger microbial population or sand or other soil particles having diameters between 0.063- and 0.042-mm.

However, regardless of dairies, the majority of solids in flushed dairy manures were found to be smaller than 0.5-mm—63.85%, 58.17%, 57.94%, and 51.50% for dairies, #1, #2, #3, and #4, respectively. The percentage would be even higher as some solids were lost during the experimental period, most of which were finer particles.

The dairy-specific statistical significances of the TS removal capacities of different pore-sized inclined screen separators can be expected since each dairy had its unique particle size distribution. Most commercial inclined screen separators have pore sizes larger than 0.5 mm, therefore, if the 0.5-mm pore sized inclined screen separators were to be used in the four dairies, the screen separators would remove only a fraction of TS from flushed dairy manures—25.41%, 33.52%, 31.86%, and 37.40% for dairies #1, #2, #3, and #4, respectively. This indicates that the dairies need to look for more advanced solid-liquid separation technologies to remove more solids from their flushed dairy manures.

The percentages of finer solids (<0.5 mm) in flushed dairy manures were found to be similar to the percentage of finer solids in raw/fresh dairy manure. During this study, about 63.85%, 58.17%, 57.94%, and 51.50% of solids particles were found to be <0.5 mm for dairies, #1, #2, #3, and #4, respectively compared to 51.1% and 60.21% of TS <0.5 mm in raw feces of dairy cows reported by Chang & Rible (1975) as reported in Zhang & Westerman (1997) and Powers et al. (1995), respectively. However, this study shows that the percentages of coarser solids (>0.25 mm) in flushed dairy manures are higher than that in raw dairy manure; 29.21%, 38.95%, 35.84%, and 42.36% >0.25 mm for dairies, #1, #2, #3, and #4, respectively compared to 25.2% TS >0.25 mm in raw cattle slurry reported by Peters et al. (2011). The higher proportions of coarser solids in flushed dairy manure compared to fresh dairy manure could be due to the mixing of bedding materials and wasted feed with manure.

Meyer et al. (2004) and Wright (2005) had investigated the particle size distribution of flushed dairy manure. In the study by Meyer et al. (2004), the dairy used wash water from milking parlor for flushing, similar to Dairy #3 during this study. However, the particle size distribution of flushed dairy manure of Dairy #3 (22.35%, 9.55%, 3.98%, 5.22%, and 48.75% TS belonging to 2-, 0.5-, 0.25-,0.125-, and <0.125-mm diameter groups) was found to be different than that observed by Meyer et al. (2004), who reported about 10.48%, 26.06%, 14.27%, 18.28%, and 30.90% of TS belonging to 2-, 0.5-, 0.25-,0.125-, and <0.125-mm diameter groups. This disparity could be due to the differences in management practices and digestive performances of animals. For the other three dairies that used recycled lagoon flush water, the higher percentages of solids <0.125 mm (57.21%, 47.82%, and 41.88% for dairies, #1, #2, and #4, respectively) can be expected because of the addition of finer solids from recycled lagoon wastewater.

Wright (2005) investigated particle size distribution of flushed dairy manure involving recycled lagoon flush water and reported about 25% of TS >0.5 mm. During this study, Dairy #1, which had closer initial TS content with the flushed dairy manure used by Wright (2005), also showed similar results with 25.41% of TS >0.5 mm. However, comparatively higher percentages of TS >0.5 mm (33.52%, and 37.40%) were observed for dairies, #2 and #4 that had higher initial solids content. This illustrates that the PSD of flushed dairy manure is site-specific as observed in Figure 4.7

5.1.5 Nutrient distribution

5.1.5.1 Total nitrogen (TN) distribution

The literature on the TN distribution of fresh dairy manure shows that most of the TN is associated with finer particles. This study also shows that most of the TN in flushed dairy manures are associated with finer particles irrespective of dairy. However, the percentages of TN belonging to finer diameter groups in flushed dairy manure—72.00%, 75.14%, 75.76%, and 61.92% TN associated with particles less than 0.5 mm diameter for dairies, #1, #2, #3, and #4, respectively—were found to be comparatively lower than that for fresh manure (86.29% TN linked to particles less than 0.5 mm diameter, observed by Powers et al., 1995). The higher percentages of TN in flushed dairy manures associated with coarser particles (26.60%, 19.56%, 19.00%, and 30.84% associated with particles larger than 1.5 mm for dairies, #1, #2, #3, and #4, respectively) compared to raw dairy manure (7.58% TN linked with particles larger than 1.0 mm reported by Møller et al., 2002) might be because of the addition of nitrogen-rich coarser wasted feed, undigested feed, and animal hairs to the flushed manure which are mostly absent in fresh dairy manure. A comparatively higher amount of larger particles that were present in flushed dairy manures could also trap some nitrogen-rich finer particles, thus leading to higher TN content associated with coarser solids. Lindley (1970), as reported in Zhang & Westerman (1997), had argued that the finer manure solids decompose faster than coarser solids. Therefore, the faster decomposition of finer solids in lagoon and volatilization of nitrogen in form of ammonia might have reduced the nitrogen content associated with finer particles, and as a result, the effect of the addition of nitrogen-rich coarser particles might have been more pronounced than the contribution of finer particles toward the TN distribution.

The reasons for the different percentages of TN associated with the same-sized particles in different dairies can be attributed to the differences in the dairy management practices and digestive performances of the cows across the four dairies. Van Horn (1998) and Wright (2005) also attributed the variations in TN content with particle size to the difference in organic nitrogen content in feed and the digestibility of animals. Mixing of bedding materials and spilled feed and the extent of dilution could have also impacted the nutrient composition and distribution in flushed dairy manures of the four dairies (Hjorth et al., 2011; Zhang, 2002).

The presence of the highest percentage of TN associated with solids <0.001 mm diameter group for all four dairies indicates that most of the TN in flushed dairy manure is associated with finer solids. The solids belonging to 4-, 2-, 0.5-, and 0.25-mm diameter groups also had a considerable percentage of TN associated with them in all four dairies. The coarser solids most probably resulted from bedding materials, spilled feedstuff, or undigested feed, of which the undigested and wasted feedstuffs are rich in TN. Likewise, the trapping of more nitrogen-rich finer solids by such larger particles could have also contributed to this. These two reasons also explain the highest percent of TN associated with solids larger than 0.5 mm in the case of Dairy #4 compared to the other dairies as Dairy #4 had the highest percent of TS larger than 0.5 mm.

The lower percentage of solids present between the 0.042- and <0.001-mm diameter groups (Figure 4.3, Figure 4.4, Figure 4.5, and Figure 4.6) for all four dairies could have resulted in the lower amount of TN (and TP as well) (Figure 4.8, Figure 4.9, Figure 4.10, and Figure 4.11) observed between those two diameter groups.

An interesting observation was found at the 0.042 mm diameter group for Dairy #4. Although Dairy #4 had a considerably higher percentage of solids associated with 0.042 mm diameter group compared to other dairies, the percentage of TN that was observed at 0.042 mm diameter group was quite low. This could be due to the presence of a large microbial population at this diameter group or due to the presence of some sand or soil particles of around 0.042 mm size which do not carry much nitrogen with them. This was also the case for the percentage of TP observed at the 0.042 mm diameter group for Dairy #4.

The varying TN distribution of the flushed dairy manures of the four dairies resulted in the dairy-specific statistical significances of the TN removal capacities of different pore-sized inclined screen separators. Since most of the TN in the flushed dairy manures of all four dairies were associated with solids finer than 0.5 mm in diameter, a commercial 0.5-mm pore sized inclined screen separator would remove only a fraction of TN from the flushed dairy manures of the four dairies (28.00%, 24.86%, 24.24%, and 38.08% from dairies, #1, #2, #3, and #4, respectively) indicating that dairymen might need to look beyond the 0.5-mm pore sized inclined screen separator to remove more TN from their flushed dairy manures.

5.1.5.2 Total phosphorous (TP) distribution

The overall variation in the distribution of TP in flushed dairy manures of the four dairies could be attributed to the differences in the nutrient content of feed supplied to the cattle, digestive and assimilative powers of the cattle, mixing of bedding materials, wasted feedstuffs, and animal hairs to the manure, the extent of dilution, etc. This variation led to the dairy-specific statistical significances of the TP removal capacities of different pore-sized inclined screen separators.

The highest percent of TP observed at <0.001 mm diameter groups for all four dairies shows that most of the TP in flushed dairy manures are associated with finer particles. The higher percent of TP (7.79–31.39%) associated with solids of diameters between 0.063- and <0.001-mm diameter groups for all four dairies compared to TN (4.57–16.46%) also shows that TP is mostly associated with finer solids in flushed dairy manures.

As expected, because of the lower percentage of TS belonging to solids of diameters between 0.063 mm and <0.001 mm in flushed dairy manures of all four dairies, the percentage of TP associated with solids between the two diameter groups was also low.

The solids belonging to the 4-, 2-, 0.5- and 0.25-mm diameters groups also had a considerable amount of TP associated with them, which is also expected as such larger particles most probably originated from either bedding material, undigested feed, or spilled feedstuffs, of which undigested and spilled feedstuff are rich in TP. The trapping of finer particles that are rich in TP content by larger particles could have also contributed to this. These two reasons also explain the highest percent of TP associated with solids >0.5 mm diameter in the flushed dairy manure of Dairy #4 as Dairy #4 had the highest percentage of solids >0.5 mm in its flushed dairy manure.

Irrespective of dairy, most of the TP in flushed dairy manure of all four dairies were associated with finer particles (85.64%, 70.58%, 69.28%, and 61.35% of TP belonging to the solid particle <0.5 mm for dairies, #1, #2, #3, and #4, respectively). Regarding the TP linked with solids >0.5 mm, the maximum percentages of TP that would be removed from the flushed dairy manures of dairies, #1, #2, #3, and #4 by 0.5-mm pore-sized inclined screen separators were found to be 14.36%, 29.42%, 30.72%, and 38.65%, respectively indicating a need for more advanced solid-liquid separation technologies for removing higher amounts TP from flushed dairy manures.

Compared to raw manure, a lower percentage of TP was observed to be associated with finer particles in flushed dairy manures. During this study, the percentages of TP passing via 0.125 mm sieve were around 77.71%, 64.09%, 61.15%, and 44.96% for dairies, #1, #2, #3, and #4, respectively. Meyer et al (2007) and Wu & Zhong (2020) found 86.73% and 81.45% of TP present in fresh dairy manure of lactating cows passing through 0.125- and 0.15-mm pore-sized sieves, respectively. The percentages of TP associated with particles >0.5 mm during this study (14.36%, 29.42%. 30.72%, and 38.65% for dairies, #1, #2, #3, and #4, respectively) were also higher than that observed by Powers et al. (1995) (5.67% TP associated with particles >0.5 mm) in fresh feces of dairy cows. The higher percentages of TP associated with larger particles in flushed dairy manures compared to fresh dairy manure could be due to the mixing of coarser bedding materials and spilled feedstuffs containing higher TP content to the flushed manure.

5.2 Summary and conclusions

The information on particle density and distribution of solids and nutrients in flushed dairy manure is critical for selecting effective manure treatment technologies and devising better manure nutrient management plans. The knowledge of particle density and particle size distribution of flushed dairy manure is indispensable for designing pumps, solid-liquid separation equipment, and storage tanks and estimating the energy required for pumping. Likewise, the information on nutrient distribution would be useful for making better nutrient management plans on dairy farms.

This study aimed to investigate the particle density, particle size, and total nitrogen and total phosphorous distributions of flushed dairy manure by taking the case studies of four commercial dairies in Southern Idaho. The goal was also to examine the statistical significance of using different pore-sized inclined screen separators for solids and nutrients removal from flushed dairy manures of the four dairies.

The particle densities of flushed dairy manure solids were determined using the standard pycnometer method with methanol medium. Due to the lack of a standard method for linking the particle size with nutrient distribution in livestock manures, a new technique—wet sieving combined with hydrometer-pipette analysis—was adopted in this study. The Hach methods, TNT 880 for TN and TNT 845 for TP were used for the nutrient analyses.

The flushed dairy manures of the four dairies differed in the initial total solid as well as nutrient contents with TS ranging from 2.23% to 7.69%, TN ranging from 0.08% to 0.19%, and TP ranging from 0.04% to 0.13%. The particle densities of flushed dairy manure solids varied with particle size, and the average particle densities of flushed dairy manure solids of the four dairies were found to be 1.49, 1.36, 1.37, and 1.30 g/cm^3 for dairies, #1, #2, #3, and #4, respectively, much lower than the commonly used particle density of soils of 2.65 g/cm^3. The study revealed that the particle size and nutrient distributions of flushed dairy manure are dairy-specific. However, regardless of dairy, the majority of solids, TN, and TP in flushed manures were observed at diameters smaller than 0.5 mm. Dairies, #1, #2, #3, and #4 had 63.85%, 58.17%, 57.94%, and 51.50% of TS smaller than 0.5 mm in diameter. Similarly, the percentages of TN and TP associated with particles smaller than 0.5 mm in diameter for dairies #1, #2, #3, and #4 were found to be 72.00%, 75.14%, 75.76%, and 61.92% of TN and 85.64%, 70.58%, 69.28%, and 61.35% of TP, respectively. The percentages of TS, TN, and TP belonging to solids of finer diameter groups would be even higher as some solids were lost during the experimental period, most of which were finer particles. The statistical differences between the solid and nutrient removal capacities of different pore-sized inclined screen separators were found to be dairy-specific.

From this study, it was estimated that the 0.5-mm pore-sized inclined screen separators would remove between 25.41% and 37.40% of TS, 24.24% and 38.08% of TN, and 14.36% and 38.65% of TP from flushed dairy manures with initial TS ranging from 2.23% to 7.69%. This shows that commercial inclined screen separators with screen pore size larger than 0.5 mm can remove only a fraction of total solids, total nitrogen, and total phosphorus from flushed dairy manures, and the majority of solids and nutrients would remain in the liquid fraction after solid-liquid separation. Therefore, the dairy farmers that rely on inclined screen separators with pore sizes larger than 0.5 mm for solid-liquid separation might need to look at more advanced solid-liquid separation technologies including centrifugation, filtration, or even membrane separation processes like micro-, ultra-, and nano-filtration or reverse osmosis to remove higher quantities of solids and nutrients from their flushed dairy manures.

5.3 Limitations of the study

Several methods including wet sieving, resonance mass measurement, electrolyte resistance, sequential ultra/nanofiltration, laser diffraction, particle image analysis, high-performance chromatography, and size exclusion chromatography (Arimi, 2018) are commonly used to determine the particle size and nutrient distribution of domestic, municipal, and industrial wastewaters. However, there has not been an agreed standard method for analyzing the particle size distribution of animal manure, and Christensen & Sommer (2013) argued that the characterizations of biowaste particles are arbitrary. Due to the high variability, complex composition, and perpetual microbial activity in manure, the precise quantification of particle size and nutrient distribution is difficult (Wright, 2005), and previous studies have reported imbalances in the mass balance of solids during PSD analysis—Peters et al. (2011) observed a 3% loss of dry matter and overestimation of dry matter by up to 40% during the PSD analysis experiments, while Meyer et al. (2007) found ±1% error. The method adopted during this study—combining wet sieving and hydrometer analysis methods—for determining the particle size as well as the nutrient distributions of flushed dairy manure also has some limitations because of the loss of some solids during the study. Several factors could contribute to these errors throughout the whole experimental period.

1. The continuous breakdown of manure solids due to microbial activity (Christensen & Sommer, 2013) causes loss of TS and TN content throughout the study period. The temperature of flushed dairy manures rose to 22°C during the experiment. There were some froths observed on the liquid surface at the end of the hydrometer analysis experiment after 24 hours, which probably could have been due to the microbial activity.
2. During the wet sieving process, the duration of stirring could impact the amount of solids passing through each sieve; if stirring is inadequate, larger solids might block the pores preventing the passage of smaller particles, and vigorous stirring can also break down larger particles (Wright, 2005).
3. Deflocculating agents were not used during the hydrometer method because of potential interference of other ions or compounds on settling of solids by combining with manure particles. The deflocculating agents like sodium hexametaphosphate could also impact the nutrient analysis data. The absence of deflocculating agent during the

hydrometer method could impact the settling velocity of solids and thus, the recorded specific gravity values and calculated particle diameters of manure solids.

4. 10 ml samples taken out for nutrient analysis during the wet sieving method takes away some of the solids introducing some errors during the mass balance.
5. The loss of the small amount of solids attached to the inner walls of the flask during the sieving process, or the surface of the hydrometer and temperature probe during the hydrometer method could also introduce some errors in the experiment.

5.4 Implications of the study

The main objective of this study was to identify the particle density, particle size, and nutrient distribution of flushed dairy manure using four commercial dairies in Southern Idaho as case studies. Therefore, this study has some major implications for the four dairies. The findings would be valuable for dairymen of the four dairies while selecting and implementing proper manure treatment technologies and devising better manure nutrient management plans on their farms. Although compositions and characteristics of flushed dairy manure vary with dairies as observed during this study, other dairies that have dairy management practices and initial total solid and nutrient contents in flushed dairy manure like that of the four dairies reported in this study would also benefit from this work. The literature on the particle density, particle size, and nutrient distribution of flushed dairy manure is scant. Thus, this study would contribute to enhance the body of literature in the field of manure management.

5.5 Suggestions and recommendations for future research

The information on the particle density, particle size, and nutrient distribution of flushed dairy manure is scarce. As the composition of flushed dairy manure greatly depends on animal biology and dairy management practices, more studies on other dairy farms that also use the flush system, especially ones using recycled lagoon flush water, in varying climatic, spatial, and management conditions are required to enhance the body of information in this field. The distribution pattern of solids and nutrients in flushed dairy manure might vary with seasonal changes. Therefore, the seasonal variation in the particle size and nutrient distribution could be an area for future studies. There is no standard method for linking the particle size with nutrient distribution in livestock manure for finer particle diameters, and this study used a new technique—combining wet sieving, hydrometer, and pipette methods—for linking nutrients with particle size distribution. Improving the degree of accuracy of the method adopted during this study by minimizing the loss of solids or devising a whole new standard method that could be universally adopted is a requirement in this field.

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