GEOTEXTILE FILTRATION PERFORMANCE FOR LAGOON SLUDGES AND LIQUID ANIMAL MANURES DEWATERING

K. B. Cantrell, J. P. Chastain, K. P. Moore

ABSTRACT. *Maintenance and control of liquid levels in anaerobic lagoons and storage ponds is enhanced by pretreatment with liquid-solid separation or periodic removal of accumulated sludges. Until local disposal or nutrient recycling options become available, sludges can be contained, dewatered, and stored using geotextile filtration. A geotextile filtration testing method termed a hanging-bag test was used to treat dairy lagoon sludge, swine lagoon sludge, liquid dairy manure, and liquid swine manure. Hanging-bag performance was evaluated by: (1) determining solids and plant nutrient mass retention efficiencies (MRE), (2) quantifying the overall volume reduction, and (3) characterizing the dewatered manure. After three fill-dewater cycles, geotextile filtration performed similarly for the sludges, retaining an average 87.6% of total solids (TS), 58.4% of total ammoniacal nitrogen (TAN), and 86.7% total phosphorous (TP). Geotextile filtration was also effective in dewatering and concentrating the sludges; by highly concentrating the retained solids, it reduced the total influent sludge volume requiring disposal to less than 18.5%. Despite relatively high MRE values for liquid swine manure (70.2% of TS, 65.1% of TAN, and 75.7% of TP), geotextile filtration was ineffective as a primary liquid-solid separation, with 60.3% of the total influent volume remaining. For liquid dairy manure (TS = 0.71%), geotextile filtration reduced the total influent volume to less than 1%, concentrated the solids and nutrients in the dewatered material 16 to 21 times greater than the influent, and retained 38.4% of TS, 25.8% of TAN, and 45.0% of TP, making this an effective liquid-solid separation technique.*

Keywords. *Animal waste, Liquid-solid separation, Manure treatment, Mass removal, Nutrient management, Wastewater.*

In many regions of the U.S., anaerobic treatment lagoons and storage ponds are common structures used to treat and store dairy and swine manures. Anaerobic lagoons are sized to include: (1) anaerobic treatment volume; (2) manure and wastewater storage volume; (3) volume for net rainfall (precipitation - evaporation) and rain from a 25-year, 24-hour event; (4) a free board of at least 0.384 m (*ASAE Standards*, 2002); and (5) sludge storage. Unfortunately, sludge storage management is often an underestimated factor in lagoon management. Accumulation of excess sludge reduces the available treatment volume, which consequently slows the biological decomposition of the volatile matter and creates strong odors (Chastain and Linvill, 1999). In order to circumvent this problem, periodic removal of accumulated sludge is necessary (Chastain and Henry, 1999). Currently, there are limited cost-effective methods available to remove, dewater, and store lagoon sludge until it can be properly utilized or land applied.

Prolonging the functionality of a treatment lagoon or anaerobic digester can be achieved by removing part of the total and volatile solids from the influent waste stream, thereby greatly reducing sludge build-up (Chastain et al., 1999; Mukhtar et al., 2004). For any anaerobic treatment process, solid separation of liquid dairy and swine manures via gravity settling can greatly reduce the organic loading. Depending on the design of the gravity settling basin, the settled solids can have high water content and must be handled as a slurry (Chastain et al., 2001a; Chastain et al., 2001b). As such, the undigested manure with a total solids (TS) content in the range of 5% to 13% can lead to odor and fly problems.

The removed sludge and separated solids can be land applied to local crop or pasture land to utilize the inherent plant nutrients. In many instances, nutrient management plans can limit application to crop or pastureland near the animal facility to reduce potential overapplication (Stone et al., 1998). If nutrient management plans influence land application, then the separated solids or high moisture content sludge are usually hauled to remote fields. This action leads to high transportation and labor costs. A significant decrease in moisture content would greatly reduce the volume for costly transportation, thereby reducing the economic burden of lagoon maintenance and renovation. In addition to dewatering, geotextile bag filtration may provide a means for intermittent storage of both lagoon sludge and gravity-separated solids when land application alternatives are not immediately available.

Geotextile filtration uses high-strength permeable geotextiles with uniquely designed retention properties fabricated into closed geocontainers. Typically, the chosen fabric is in-

---

Submitted for review in October 2007 as manuscript number SE 7213; approved for publication by the Structures & Environment Division of ASABE in March 2008. Presented at the 2002 ASABE Annual Meeting as Paper No. 024128.

The authors are **Keri B. Cantrell, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS, Florence, South Carolina; **John P. Chastain, ASABE Member Engineer,** Professor, Department of Agricultural and Biological Engineering, Clemson University, Clemson, South Carolina; and **Kathy P. Moore,** Director, Agricultural Services Laboratory, Clemson University, Clemson, South Carolina. **Corresponding author:** Keri B. Cantrell, USDA-ARS, 2611 West Lucas St., Florence, SC 29501-1242; phone: 843-669-5203, ext. 113, fax: 843-669-6970; e-mail: keri.cantrell@ars.usda.gov.

ert to biological degradation and resistant to naturally encountered chemicals. Geotextile filtration operates in three basic steps: (1) confinement, (2) dewatering, and (3) consolidation. The geotextile weave creates small pores that confine the fine and coarse particles of the contained material. The small pores allow excess water to escape, resulting in reduction of both moisture content and volume. This volume reduction allows repeated filling of the geocontainer; after the final cycle of filling and dewatering, the retained materials can continue to consolidate because residual water vapor escapes (Fowler et al., 1997; Moo-Young et al., 2002).

When used in conjunction with dairy and swine liquid manure handling systems using gravity settling and other solid separation techniques, application of this technology would allow for additional storage time for further settling and dewatering of the separated solids. Since the solids are safely contained within a geotextile bag, the odor and pest problems, such as flies, commonly associated with lagoons and storage structures (Chastain et al., 2001a) are reduced. The prolonged containment offers flexibility in the time of application, e.g., when weather conditions, crop needs, or transportation options are better suited (Worley et al., 2004). In order to maximize the confined solids, geotextile filtration requires multiple filling and dewatering cycles; thus, the overall volume reduction of sludge and separated solids would significantly reduce land application costs as well as transportation costs to remote areas (Fowler et al., 1997; Muthukumaran and Ilamparuthi, 2006).

Successful applications of geotextile dewatering technology have been demonstrated in the field and include: sandy silt (Koerner and Koerner, 2006), contaminated sediment (Moo-Young et al., 1999), sewage sludge (Fowler et al., 1997), and dairy lagoon sludge (Worley et al., 2004; Mukhtar et al., 2007). Full-scale geotextile filtration tubes approximately 5.5 × 30.5 m treating dairy lagoon sludge (TS = 6.4%) were evaluated by Worley et al. (2004) and reported to have mass-based separation efficiencies of 97% for total solids (TS), 80% for total Kjeldhal nitrogen (TKN), 92% for organic nitrogen (Org–N), 79% for phosphorous (expressed as P_2O_5), and 36% for potassium (expressed as K_2O). Another full-scale study using two 4.3 × 15.2 m tubes treating dairy lagoon slurry (TS = 6.0%) with alum (Al_2SO_4) was effective in retaining 94.7% of TS and improved the mass-based separation efficiency, or mass retention efficiency, for TKN and total phosphorous to 85.1% and 96.9%, respectively (Mukhtar et al., 2007). The study by Worley et al. (2004) concluded that keeping the tube full by refilling on a regular basis reduced the time to complete the dewatering process. Approximately four weeks were necessary to maximize the solids contained in a tube, with another two to four weeks of dewatering to ensure that the dewatered material could be handled as a solid. Meanwhile, the filtered effluent, or filtrate, was directed back into the lagoon to restore treatment volume.

While previous full-scale, agricultural efforts have focused on sludge dewatering, the goal of this study was to expand the evaluation and compare the performance of using geotextile filtration for the dewatering of four animal wastes: dairy lagoon sludge, swine lagoon sludge, liquid dairy manure, and liquid swine manures. The three specific objectives of this study were to:

1. Determine differences in the solids and plant nutrient mass retention efficiencies (MRE) between fill-dewater cycles and manure type.
2. Quantify the overall volume reduction (VR_3)for each manure type.
3. Characterize compositional differences among the geotextile dewatered material.

MATERIALS AND METHODS

ANIMAL MANURE COLLECTION

The following four types of manure were used for the experiment: dairy lagoon sludge, swine lagoon sludge, liquid dairy manure, and liquid swine manure. The dairy and swine sludge samples were a slurry-mix obtained from well-mixed lagoons located on Clemson University Experiment Station farms and consisted of a mix of supernatant liquid and sludge. Both of these lagoons were receiving untreated manure directly from the livestock facilities.

The liquid dairy manure sample, from Orangeburg County, S.C., was acquired from a milking parlor on a dairy farm and consisted of dairy manure, waste milk, and water used for flushing the floors, bulk tank, and pipeline (Chastain et al., 2005). All of this wastewater was transferred from the milking center and stored in an adjacent, uncovered, below-ground, concrete holding pit. At weekly intervals, the contents of the pit were agitated and emptied, during which time a sample was collected.

The liquid swine manure sample was directly obtained at the Starkey Swine Center at Clemson University from the slurry pit of a 300-head finishing barn. This barn was an open-front building with a solid, sloped floor. The slurry pit was located both adjacent to the sloped resting area and below a slotted floor. From this slurry pit, a submersible centrifugal pump with a combination PVC pipe and flex hose outlet was used to transfer the liquid swine manure to a trailer-mounted tank.

Upon collection, each manure type was loaded into a trailer-mounted collection tank and transported to an open-front shed at the Starkey Swine Center (the experiment site). Once on location, each of the four types of manure was transferred using a submersible pump into separate, sealed polypropylene storage tanks.

DESCRIPTION OF SITE CONFIGURATION AND APPARATUS

Geotextile filtration solids and plant nutrient retention of the sludges and manures was estimated using three replications in each hanging-bag test. The hanging-bag test, a modified version of the method proposed by Fowler et al. (1994), permitted precise measurement of solids content, plant nutrient content, and volumes of both the influent and filtrate. The geotextile fabric used to manufacture bags with average lay-flat dimensions of 0.44 × 1.7 m (Mirafi Division of Ten Cate Nicolon USA, Pendergrass, Ga.) had a permittivity of 0.40 L s^{-1}, an apparent opening size (AOS) of 0.600 mm, and ultimate tensile strength of 70.0 kN m^{-1}. Selection of this fabric was based on findings of a preliminary experiment using dairy lagoon sludge (TS = 125 g L^{-1}) conducted to evaluate the influence of geotextile fabric weave on volume reduction (Baker, 2002). The results indicated that the AOS influenced the dewatering rate and not the final volume reduction; all three fabrics tested (AOS = 0.300, 0.425, and 0.600 mm) provided the same final volume reduction.

The experimental configuration for the current study consisted of the four sample storage tanks and a water rinse tank

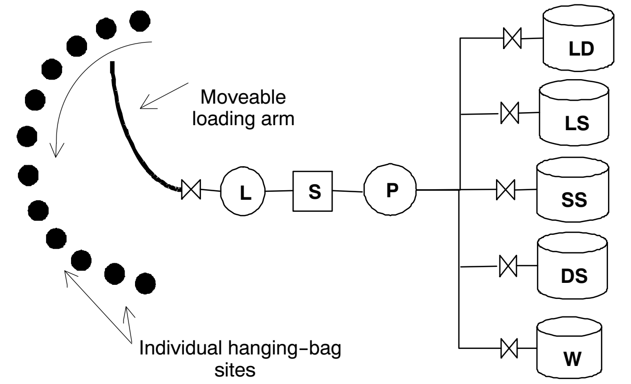


Figure 1. Schematic of the hanging-bag test: L = elevated loading tank, S = sampling port, P = pump, LD = liquid dairy manure holding tank, LS = liquid swine manure holding tank, SS = swine lagoon sludge holding tank, DS = dairy lagoon sludge holding tank, and W = clean rinse water holding tank.

connected via a PVC pipe manifold system (fig. 1). This manifold system included the required valves to allow the selected material to be pumped into an elevated 189 L calibrated loading tank. The elevated loading tank had a conical bottom and was calibrated using water to determine the inverse relationship, according to the quadratic equation shown (eq. 1), between the loading tank volume, V_{tank} (L), and the distance between the lip of the tank to the height of the liquid, D (cm). This regression had an R^2 value of 1.00 and a standard error of the y-estimate ($S_{x,y}$) of ±0.797 L:

$$V_{tank} = 0.019D^2 - 4.642D + 188.48. \tag{1}$$

Located at the base of the loading tank were a ball valve and a flex-hose/PVC-pipe moveable arm. The ball valve allowed outflow control, while the moveable arm allowed easy positioning over the 12 geotextile bags suspended in wooden frames and arranged on the moveable arm's radius (fig. 1). While large containers underneath the bags continuously collected filtrate (fig. 2), plastic sheeting surrounding the wooden frames kept ammonia volatilization losses to a minimum (Baker, 2002). In the previous preliminary hanging-bag test, total ammoniacal nitrogen (TAN) concentrations were calculated through mass balance and via direct measurement. The very small differences between these two measurements were found to be within the coefficient of variation of the influent and filtrate concentration measurements. Therefore, it was assumed that the volatilization losses were within TAN concentration measurement errors; consequently, this assumption was applied to the current study.

INFLUENT LOADING AND SAMPLING PROCEDURE

After flushing the loading tank three times with tap water and then three times with a selected manure, approximately 50 L of well-mixed influent was collected from the sampling port (S in fig. 1) located between the pump and loading tank to represent the influent. In order to have a well-mixed influent sample during loading, a recirculation pump was placed inside the storage container and operated continuously. Then, a predetermined volume of influent, based on the measurement of D (eq. 1), was loaded into the bag. A foam float attached to monofilament line and suspended in the loading tank served as a visual indicator when the desired D value was reached. After filling the calibrated loading tank, a second average depth measurement was recorded to determine the actual V_{tank} value transferred to each bag. Finally, the ball valve was opened quickly to cause a high inlet flow rate through the moveable arm and scour the settled solids, thereby ensuring that all solids entered the bag.

Figure 2. Geotextile bag (center) and frame used to conduct a hanging-bag test.

FILTRATE COLLECTION AND SAMPLING PROCEDURE

Volumetric measurement and subsampling of filtrate in the large collection containers at the base of each of the 12 bags tested occurred within 4 h of each loading and then daily thereafter. The filtrate volumes were measured using graduated cylinders that varied in size from 100 to 4000 mL, resulting in an overall uncertainty of ±0.250 L in the total filtrate volume measurements at that measurement interval. Once the measured filtrate volume was significantly less than the initial daily measurements (i.e., less than half the volume measured compared to the second or third day), the collection intervals were extended to every two to three days. Filtrate measurements and subsampling were ceased when a collection interval yielded less than 100 mL. Depending on treatment, this occurred within 8 to 30 days of loading, at which time the fill-dewatering cycle for that geotextile bag was considered complete.

At each measurement interval, a well-mixed filtrate subsample from the measured filtrate with a volume between 250 to 1000 mL was collected. The volume of filtrate subsample collected at the beginning of a fill-dewater cycle was 1 L. As a fill-dewater cycle progressed and the filtrate volume decreased, smaller sample volumes were collected. For each dewatering cycle, this subsampling was performed in order to: (1) reduce the volume of filtrate retained, and (2) create a representative composite filtrate sample.

At the end of a fill-dewatering cycle for each bag, composite filtrate samples for solids and plant nutrient analyses were made by combining all filtrate subsamples using a volumetric weighted average. The volume of subsample added to a composite sample was weighted based on the volume of filtrate released during a time interval to the total filtrate released over the entire dewatering cycle. All samples were stored on ice and transported to the laboratory and stored in a refrigerator at 4°C until analyzed.

MULTIPLE FILLINGS AND DEWATERED MATERIAL REMOVAL

Once filtrate volumes were negligible, additional waste was added to return the bag volume to approximately its initial influent volume. This procedure was repeated twice, for three fill-dewatering cycles per bag. Multiple fills were executed to simulate recommended operation of full-scale bags to maximize retained solids (Fowler et al., 1997; Worley et al., 2004). At the end of the third fill-dewater cycle, each bag was cut open, rendering it useless for another fill-dewater cycle. All the contents were drained into a separate container and mixed well. A representative sample approximately 3.5 L of dewatered material was collected and stored at 4°C.

ANALYTICAL METHODS

Standard oven drying and furnace incineration techniques (APHA, 2005) were used for the total solids (TS) and volatile solids (VS) analyses of the influent, filtrate, and dewatered solid samples. Total solids is the sum of total suspended solids (TSS) and total dissolved solids (TDS), while VS is the sum of volatile suspended solids (VSS) and volatile dissolved solids (VDS). Within a fill-dewater cycle, dissolved concentrations TDS and VDS were assumed constant from the influent to the filtrate. Thus, TDS and VDS concentrations of the filtrate sample were quantified. Due to the influents' poor filtering characteristics (a 0.45 µm filter would clog quickly, passing little volume), TSS of the influent was calculated as the difference between the influent TS and filtrate TDS (TSS = TS - TDS). The VSS concentrations were computed similarly: VSS = VS - VDS.

Representative influent, composite filtrate, and dewatered solids samples were analyzed to determine the concentration of the following plant nutrients: total Kjeldhal nitrogen (TKN), total ammoniacal nitrogen (TAN = $NH_4{}^+$-N + NH_3-N), total phosphorous (expressed as P_2O_5), K_2O, calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), copper (Cu), manganese (Mn), and sodium (Na). The difference between TKN and TAN determined the organic nitrogen (Org-N). Plant nutrient analyses were provided by the Agricultural Service Laboratory at Clemson University and conducted following the general procedures outlined by Peters et al. (2003). Bulk density of the influent and dewatered materials (ρ_M) was measured in-house using an aluminum container of known volume and mass.

PARAMETER ESTIMATIONS

Mass Reduction

Application of the conservation of mass of constituent *j* (i.e., the measured solids and plant nutrients; table 1) remaining in a geotextile bag at the end of each fill-dewater cycle, $M_{N\text{-}bagj}$, is a cumulative parameter through successive fill-dewater cycles and is represented by the following equation:

$$M_{N-bagj} = \sum_{i=1}^{N} M_{INji} - \sum_{i=1}^{N} M_{OUTji} = \sum_{i=1}^{N} C_{IN_{ji}} V_{IN_i} - \sum_{i=1}^{N} C_{OUT_{ji}} V_{OUT_i} \quad (2)$$

where

N = number of fill-dewater cycles completed (N = 1, 2, 3)

M_{INji} = total mass of any constituent *j* added to the bag for a fill-dewater cycle *i*

M_{OUTji} = total mass of any constituent *j* that passes through the geotextile fabric in the filtrate for a fill-dewater cycle *i*

C_{INji} = influent concentration of constituent *j* for fill-dewater cycle *i*

V_{INi} = influent volume for fill-dewater cycle *i*

C_{OUTji} = filtrate concentration of constituent *j* for dewatering period *i*

V_{OUTi} = total filtrate volume for dewatering period *i*.

Dividing $M_{N\text{-}bagj}$ by the mass of constituent *j* added to the bag ($M_{N\text{-}INj}$) up to fill dewater-cycle *i* yields the mass retention efficiency for a fill-dewater cycle (MRE_N):

$$\text{MRE}_N = \frac{M_{N-bagj}}{M_{N-INj}} \cdot 100 \quad (3)$$

In this respect, MRE_N is a cumulative parameter; part of the influent material loaded during the first fill filters continuously throughout the entire experiment. Within a replication for a defined manure treatment, it is impossible to separate the effects of the first fill from subsequent fills; therefore, the removal efficiency after completing the third fill (MRE_3) is the overall mass retention efficiency.

In order to determine difference among averaged MRE values between three fill-dewater cycles and four manure treatments, a 3 × 4 factorial analysis of variance (ANOVA) and a least significance difference test (LSD) at the 95% level were performed using Version 9.1 of SAS (SAS Institute, Inc., Cary, N.C.).

The concentration reduction across the geotextile fabric (influent to filtrate) of an individual constituent *j* (CR_j) is another parameter for evaluating geotextile filtration performance. The overall CR_j for each constituent can be computed as:

$$CR_j = \frac{\overline{C}_{IN\,j} - \overline{C}_{OUTj}}{\overline{C}_{IN\,j}} \cdot 100 \quad (4)$$

where $\overline{C}_{IN\,j}$ is the mean influent concentration constituent concentration weighted according to the influent volume for all three fill-dewater cycles, and $\overline{C}_{OUT\,j}$ is the mean filtrate constituent concentration weighted according to the filtrate volume for all three fill-dewater cycles. A concentration factor (CF_j) can similarly be calculated as the ratio of the mean dewatered constituent *j* concentration to $\overline{C}_{IN\,j}$:

$$CF_j = \frac{\overline{C}_{DWj}}{\overline{C}_{IN\,j}} \quad (5)$$

Table 1. Average influent characteristics across all fills for dairy and swine lagoon sludges and liquid dairy and swine manures.

	Dairy Sludge	Swine Sludge	Liquid Dairy	Liquid Swine
Total volume (L)[a]	254.2 (4.78)	215.0 (10.6)	284.1 (45.0)[b]	174.6 (38.3)[b]
ρ_M (g L^{-1})[c]	1005.8 (11.2)	1006.2 (11.3)	1016.0 (2.47)	990.9 (9.17)
Constituent (g L^{-1})				
TS[d]	53.367 (8.600)[e]	36.620 (0.846)	7.138 (0.909)	28.800 (3.670)
VS	16.742 (2.333)	20.741 (0.456)	4.636 (0.741)	21.232 (2.748)
TSS	51.919 (8.600)	35.159 (0.846)	4.642 (0.909)	20.531 (3.670)
VSS	16.258 (2.333)	20.361 (0.457)	3.808 (0.741)	17.701 (2.748)
TAN	0.138 (0.012)	0.393 (0.028)	0.349 (0.016)	2.718 (0.337)
Org-N	0.780 (0.091)	1.619 (0.057)	0.262 (0.081)	1.380 (0.190)
P_2O_5	1.296 (0.178)	3.308 (0.176)	0.239 (0.034)	2.165 (0.290)
K_2O	0.301 (0.020)	0.486 (0.013)	0.500 (0.042)	1.835 (0.213)
Ca	0.816 (0.113)	2.009 (0.097)	0.231 (0.027)	0.748 (0.106)
Mg	0.192 (0.024)	0.314 (0.016)	0.073 (0.009)	0.312 (0.043)
S	0.333 (0.042)	0.600 (0.025)	0.039 (0.007)	0.259 (0.031)
Zn	0.038 (0.004)	0.108 (0.005)	0.002 (0.0003)	0.042 (0.005)
Cu	0.006 (0.001)	0.015 (0.001)	0.000 (0.0001)[f]	0.005 (0.0001)
Mn	0.019 (0.002)	0.039 (0.002)	0.002 (0.0005)	0.015 (0.002)
Na	0.083 (0.004)	0.109 (0.003)	0.215 (0.010)	0.390 (0.043)

[a] Means (standard deviations); $n = 3$.

[b] Larger standard deviations due to significantly larger geotextile bag used as third replicate.

[c] Means (standard deviations); $n = 9$.

[d] TS and VS means, $n = 54$; TSS and VSS means based on constant dissolved solids concentrations for influent and filtrate, $n = 27$; Plant nutrient means, $n = 27$.

[e] Values in parentheses are standard deviations based on square root of MSE from one-way ANOVA of respective concentrations for all three fills of all three bags (Ott and Longnecker, 2001).

[f] Values shown as zero are below detection levels.

Volume Reduction

It is possible for geotextile filtration to yield high mass retention efficiency while providing very poor dewatering. Ultimately, geotextile filtration concentrates a large portion of the solids and plant nutrients in a small volume. Therefore, mass retention alone is not adequate to describe geotextile filtration's dewatering performance. A volume reduction ratio would indicate the degree to which geotextile filtration can dewater a material.

$$V_{NDW} = \sum_{i=1}^{N} V_{IN_i} - \sum_{i=1}^{N} V_{OUT_i} \qquad (6)$$

$$VR_N = \frac{V_{NDW}}{\sum_{i=1}^{N} V_{IN_i}} \qquad (7)$$

The dewatered material concentration of any constituent j (C_{DWj}) in a geotextile bag after completion of all N fill-dewater cycles can be calculated from the mass and volume balance ($M_{N\text{-}bagi}$ and V_{NDW}, respectively) as:

$$C_{DWj} = \frac{M_{N-bagj}}{V_{NDW}} \qquad (8)$$

A better estimate for the actual volume of dewatered material should take into account the volume of water evaporated (fig. 3). Thus, the actual volume of dewatered material remaining in the bag (V_{DW}*) can be calculated based on the mass balance for total solids (j = TS):

$$C_{DWTS}\ V_{3\,DW} = C_{DWTSM}\ V_{DW}\,^* \qquad (9)$$

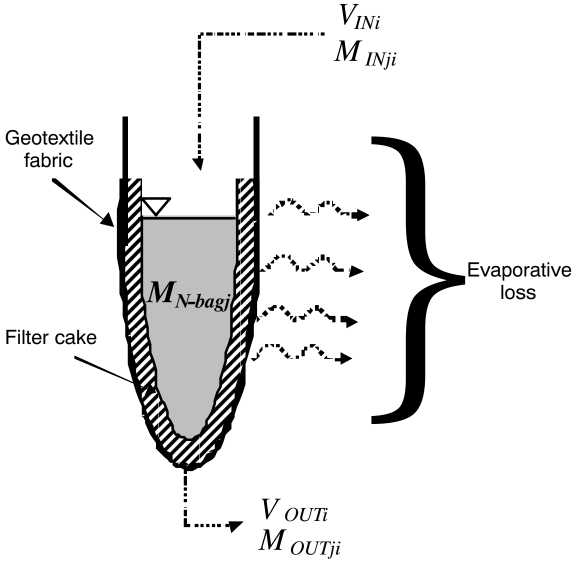


Figure 3. Schematic of the geotextile filtration process.

where

C_{DWTS} = dewatered material's TS concentration computed by mass balance (eq. 8, N = 3)

V_{3DW} = volume of the dewatered material N(eq. 6, N = 3)

C_{DWTSM} = directly measured dewatered material's TS concentration

V_{DW}* = dewatered material volume of the dewatered material that takes into account the evaporation affects.

Solving for V_{DW}* provides the following equation:

$$V_{DW}{}^{*} = \frac{C_{DWTS}}{C_{DWTSM}} V_{3DW} \qquad (10)$$

The respective volume reduction incorporating the true volume of dewatered material remaining in the bag ($VR_3{}^*$) is determined as:

$$VR_3{}^{*} = \frac{V_{DW}{}^{*}}{\sum_{i=1}^{3} V_{IN_i}} \qquad (11)$$

Results and Discussion

Characteristics of the Influent and Filtrate Materials

The average TS concentrations for the influent swine and dairy lagoon sludges ranged from 36.6 to 53.4 g L^{-1} (table 1). This was a little more concentrated than the influent liquid swine manure, which had an average TS concentration of 28.8 g L^{-1}, and was within the 13 to 73 g L^{-1} range of TS concentrations for other reported pit-recharge systems for finishing swine (Chastain et al., 2001a; Chastain et al., 1999). Due to dilution from large amounts of waste milk and water, the fresh dairy manure was the most dilute of the four materials tested, with an overall average influent TS concentration of 7.14 g L^{-1}. This TS content was less than the 17 to 38 g L^{-1} range for other reported flush dairy manure (Chastain et al., 2001b; Chastain and Camberato, 1999) and slightly more than 3.6 g L^{-1} reported for milking center wastewater (Wilkie et al, 2004).

The dairy and swine lagoon sludges contained more settleable material than their liquid manure counterparts. Their P_2O_5, Ca, S, and metals concentrations were roughly three times that of their respective counterparts. In contrast, the liquid manures contained higher concentrations of soluble plant nutrients (TAN, K_2O, and Na). These constituent differences between sludge and liquid manures are as would be expected for the more digested state of sludge and the propensity of Org–N and P_2O_5 to settle with solids (Chastain et al., 1999).

Filtrate from all of the geotextile bags contained detectable amounts of all measured constituents found to be present in the influent (table 2). Insoluble constituent concentrations were greatly reduced by geotextile filtration, while smaller declines in soluble constituent concentration were observed such as TAN, K_2O, and Na. These findings are similar to those found with high solids removal by Mukhtar et al. (2007). Removing part of TAN and VS from the influent leads to reductions in the ammonia volatilization and greenhouse gas (GHG) emissions traditionally noted for anaerobic lagoons (DeSutter and Ham, 2005; Szogi et al., 2006). However, to prevent the deleterious effect of excessive nutrient entry into surface or ground water, the total nitrogen (TAN + Org–N) and P_2O_5 filtrate concentrations would require proper containment and management.

Mass Retention Efficiency Differences Among Fill-Dewater Cycles and Manure Types

When pooling MRE values across all fill-dewater cycles and manures, calculated F values (with the exception of Zn) associated with fill-dewater cycles, with a range of 0.01 to 3.05, which was less than the required 3.316, gave no indication of statistical differences, suggesting that, for the overall experiment, MRE values were not affected by an increase in fill-dewater cycles. Fill-dewater cycles were found to improve MRE values associated with Zn for both dairy lagoon sludge and liquid swine manure.

For the overall mass retention efficiencies between manure types, all constituent MRE_3 values for liquid dairy manure were found to be significantly lower than all other materials tested (table 3). This low solids and nutrient retention was likely due to the lack of filter cake formation. There was only a thin coating of large irregular-shaped particles and

Table 2. Average geotextile filtration filtrate characteristics for dairy and swine lagoon sludges and liquid dairy and swine manures.

	Dairy Sludge	Swine Sludge	Liquid Dairy	Liquid Swine
Total volume (L)[a]	159.1 (3.09)	141.6 (8.54)	260.9 (39.4)[b]	73.3 (9.46)[b]
Constituent (g L^{-1})				
TS[c]	9.048 (1.267)[d]	6.613 (1.386)	4.888 (0.663)	19.769 (2.852)
VS	3.472 (0.457)	3.465 (0.804)	2.642 (0.427)	14.239 (2.972)
TSS	7.600 (1.267)	5.152 (1.386)	2.663 (0.663)	11.500 (2.852)
VSS	2.999 (0.442)	3.085 (0.804)	1.929 (0.427)	10.708 (2.972)
TAN	0.090 (0.014)	0.210 (0.022)	0.279 (0.022)	2.091 (0.109)
Org-N	0.184 (0.031)	0.258 (0.066)	0.162 (0.016)	0.933 (0.132)
P_2O_5	0.251 (0.031)	0.596 (0.148)	0.141 (0.013)	1.135 (0.064)
K_2O	0.250 (0.008)	0.439 (0.020)	0.542 (0.017)	2.081 (0.074)
Ca	0.156 (0.020)	0.315 (0.085)	0.165 (0.007)	0.252 (0.029)
Mg	0.055 (0.005)	0.065 (0.013)	0.052 (0.004)	0.090 (0.011)
S	0.103 (0.012)	0.156 (0.023)	0.024 (0.001)	0.156 (0.011)
Zn	0.002(0.0000)	0.020 (0.006)	0.001 (0.0000)	0.014 (0.002)
Cu	0.001 (0.0000)	0.003 (0.001)	0.000 (0.0000)[e]	0.002 (0.0001)
Mn	0.002 (0.001)	0.007 (0.002)	0.001 (0.0000)	0.005 (0.0000)
Na	0.078 (0.003)	0.107 (0.004)	0.232 (0.007)	0.455 (0.020)

[a] Means (standard deviations); $n = 3$.

[b] Larger standard deviations due to significantly larger geotextile bag used as third replicate.

[c] TS and VS means, $n = 54$; TSS and VSS means based on constant dissolved solids concentrations for influent and filtrate, $n = 27$; Plant nutrient means, $n = 27$.

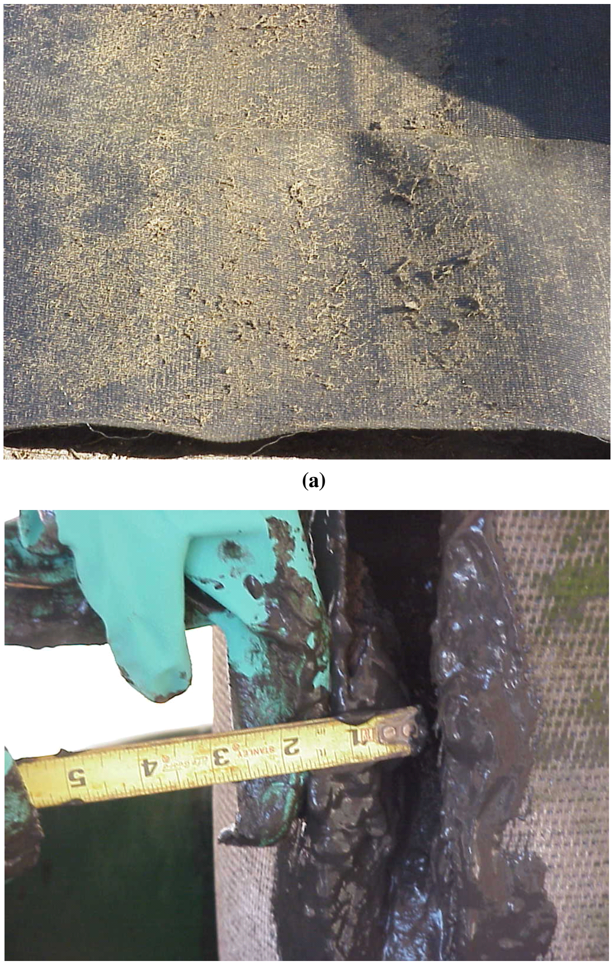
[d] Values in parentheses are standard deviations based on square root of MSE from one-way ANOVA of respective concentrations for all three fills of all three bags (Ott and Longnecker, 2001).

[e] Values shown as zero are below detection levels.

Table 3. Least significant difference (LSD) values and overall mass retention efficiencies (MRE_3) for all constituents for all manures.

		MRE_3 (%)			
Constituent	LSD[a] (%)	Dairy Sludge	Swine Sludge	Liquid Dairy	Liquid Swine
TS	4.81	87.8	87.3	38.4	70.2
VS	4.28	85.7	88.2	49.0	71.0
TSS	5.63	89.1	89.5	49.9	75.1
VSS	4.63	86.9	89.1	55.2	73.7
TAN	7.65	53.7	63.2	25.8	65.1
Org-N	4.65	85.1	88.9	43.0	69.9
P_2O_5	4.54	86.1	87.2	45.0	75.7
K_2O	6.19	48.0	41.0	0.40	50.5
Ca	4.42	86.4	88.8	34.1	83.0
Mg	4.42	80.8	85.7	34.4	84.9
S	4.12	79.2	82.7	44.2	72.6
Zn	4.89	96.0	86.8	55.8	82.6
Cu	6.82	92.8	87.3	48.4	81.8
Mn	6.61	90.2	86.4	45.5	82.8
Na	6.45	40.8	35.6	0.77	49.1

[a] LSD based on t = 2.042; a = 0.05; error degrees of freedom = 30; r = 3.


(a)

(b)

Figure 4. Filter cake formation after geotextile filtration of (a) liquid dairy manure and (b) dairy lagoon sludge.

grain-like fibers on the geotextile weave (fig. 4a). This thin film did not completely cover the geotextile pores, thus allowing liquid to pass freely.

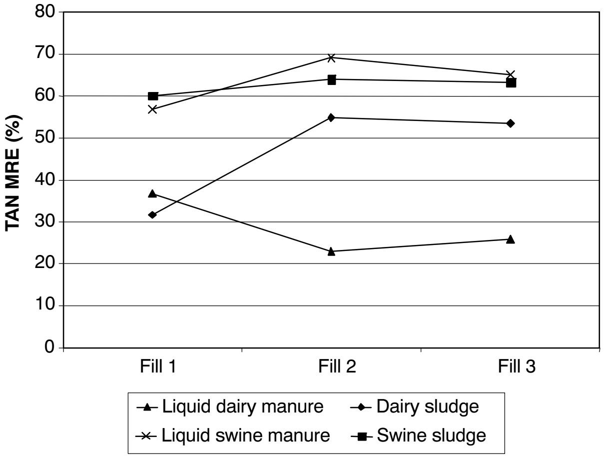


Figure 5. Average TAN mass removal efficiency (MRE) across all fill-dewater cycles for all materials.

Unlike the thin coating seen with the liquid dairy manure, both sludges had substantial filter cake formation (fig. 4b). This filter cake extended up the wall of the hanging bag above the level of the dewatered material and had a maximum thickness of 381 mm (1.5 in). This filter cake created a solid barrier that reduced the dewatering rate and aided solids and plant nutrient retention. Among the two sludges, the only significant difference between the MRE_3 values was for Mg, Zn, and K_2O, suggesting that anaerobic lagoon sludge behaves similarly during geotextile filtration. The overall retention efficiencies for swine lagoon sludge were significantly greater than for liquid swine for all constituents, except TAN, K_2O, Mg, Zn, and Na.

Of all the constituents analyzed, the MRE_3 values for soluble plant nutrients were consistently lower than the values for insoluble constituents. These low retention efficiencies can be attributed to the soluble constituents' low atomic weights and high solubility; these constituents are typically well dispersed through both the solid and liquid fractions. Consequently, large quantities of these soluble constituents are difficult to remove by physical separation processes such as filtration and screening (Zhang and Westerman, 1997). The retention efficiencies for K_2O started at 0.4% for liquid dairy manure, while the other manure's retention efficiencies had an average of 46.5%. Retention efficiencies for Na followed a similar pattern, with negligible amounts remaining in the liquid dairy manure: 38.3% for lagoon sludges, and 49.1% for liquid swine manure.

Substantial TAN retention in both sludges was again attributed to the filter cake formation (fig. 4b). As observed for high organic matter clay soils, ammonium-N (the predominant fraction of TAN) does not leach readily and is easily trapped by organic material (Brady and Weil, 1999). When comparing sludge TAN retention to the liquid dairy manure, the filter cake enhanced adhesion between the highly soluble particles (TAN, K_2O, and Na) and solids, thereby contributing to the high retention. For the liquid dairy manure, the low TAN retention efficiency was believed to occur during the second or third loadings as soluble nutrient wash-out (fig. 5). A thin film of particles and grains observed for liquid dairy manure would not be expected to catch small particles or ammonium ions in the same manner as a thick organic filter cake.

Table 4. Concentration reduction values (CR_j) for each constituent compared to overall mass retention efficiencies (MRE$_3$).

	Dairy Sludge		Swine Sludge		Liquid Dairy		Liquid Swine	
Constituent	CR_j (%)	MRE$_3$ (%)	CR_j (%)	MRE$_3$ (%)	CR_j (%)	MRE$_3$ (%)	CR_j (%)	MRE$_3$ (%)
TS	80.6	87.8	80.8	87.3	33.3	38.4	28.1	70.2
VS	77.3	85.7	82.2	88.2	44.8	49.0	30.0	71.0
TSS	82.7	89.1	84.0	89.5	45.9	49.9	39.1	75.1
VSS	79.1	86.9	83.5	89.1	51.6	55.2	36.1	73.7
TAN	26.1	53.7	44.3	63.2	19.8	25.8	15.8	65.1
Org-N	76.3	85.1	83.2	88.9	39.0	43.0	27.8	69.9
P2O5	77.9	86.1	80.6	87.2	40.4	45.0	41.2	75.7
K2O	17.0	48.0	10.2	41.0	-8.1	0.40	-18.8	50.5
Ca	78.3	86.4	83.0	88.8	28.6	34.1	58.4	83.0
Mg	69.4	80.8	78.3	85.7	28.8	34.4	62.9	84.9
S	66.9	79.2	73.8	82.7	39.4	44.2	33.5	72.6
Zn	93.6	96.0	79.9	86.8	52.3	55.8	57.4	82.6
Cu	88.6	92.8	80.7	87.3	44.2	48.4	55.9	81.8
Mn	84.5	90.2	79.3	86.4	41.2	45.5	58.0	82.8
Na	5.5	40.8	2.1	35.6	-7.6	0.77	-22.0	49.1

Concentration Reduction

Quantification of concentration reductions would serve as a useful indicator of the relative increase in the total volume of wastewater that could be land applied per unit area. With a less concentrated influent, anaerobic lagoons and gravity settling basins would be easier to manage. However, in this study, influent and filtrate volumes are not equal, and concentration reductions (table 4) alone are not sufficient to fully describe the efficacy of this geotextile filtration separation process. The CR_j values are based only on changes in concentrations across the geotextile fabric (eq. 4), whereas the MRE$_3$ values are dependent on the total constituent mass of the system, which includes both concentration and volume (eq. 3). In all but a few instances, the CR_j values were less than the MRE$_3$ values. In a few cases involving the soluble components K_2O and Na, the CR_j values were negative, indicating an increase in concentration from influent to filtrate. While this suggests uncertainty error in the concentration measurements, this increase in these highly soluble constituent's concentrations is likely due to these components easily passing through the liquid manure's filter cake (fig. 3) and exiting the system in a smaller liquid volume, i.e., the mass of Na and K_2O remained the same but the volume decreased, thereby increasing the concentration. Mass retention efficiencies were never negative since a significant volume of material was retained in all of the geotextile bags.

Volume Reduction

Except for the liquid swine manure, the geotextile filtration provided significant dewatering. In the case of the liquid swine manure treatment, dewatering was so poor that there was gravity settling within the bags. The liquid swine manure's poor dewatering characteristics were attributed to an oily build-up on the outside of the geotextile bags that clogged the weave's openings. The oily build-up was believed to be from undigested vegetable oil in the ration fed to the finishing swine. The addition of a flocculent to liquid swine manure would likely have eliminated this problem and provided favorable dewatering results (Worley et al., 2004).

Table 5. Comparison of the volume reductions observed by mass balance with values corrected to account for evaporation from the surfaces of the hanging geotextile bags.

	Dairy Sludge	Swine Sludge	Liquid Dairy
V_{3DW} (L)[a]	95.2 (3.7)[b]	73.5 (6.3)	67.8 (33.1)
VR_3[c]	0.374 (0.005)	0.342 (0.019)	0.077 (0.023)
C_{DWTS} (g L^{-1})[d]	128.8 (12.9)	93.5 (6.3)	67.8 (33.1)
C_{DWTSM} (g L^{-1})[e]	299.3 (22.7)	152.7 (2.81)	129.5 (3.39)
V_{DW}* (L)[f]	41.3 (6.6)	45.1 (4.0)	9.8 (2.1)
VR_3*[g]	0.162 (0.021)	0.209 (0.008)	0.036 (0.011)
t3 (days)[h]	70	70	33

[a] Volume of dewatered material calculated from mass balance (eq. 6).

[b] Values in parentheses are standard deviations.

[c] Volume reduction using mass balance results (eq. 7).

[d] Total solids concentration in the dewatered material based on mass balance (eq. 8, $N = 3$).

[e] Total solids concentration in the dewatered material from direct sampling.

[f] Volume of dewatered material corrected to account for evaporation losses (eq. 10).

[g] Volume reduction corrected to account for evaporation losses (eq. 11).

[h] Time for all three fill-dewater cycles as performed in this study.

After analysis of the dewatered sludges and dewatered liquid dairy manure, the TS concentrations computed by mass balance (C_{DWTS}; eq. 6) were much lower than those observed from direct measurement, C_{DWTSM}. This finding is likely related to evaporation and supported by visual observations of the condition of the geotextile fabric after dewatering (fig. 4b). Observations indicated that the mass of any constituent retained was not only inside the bag, but also entrapped in both the fabric openings and on the geotextile exterior surface. Since mass transfer occurred from within the bag to the surface of the bag, the geotextile fabric allowed significant amounts of surface water to evaporate (fig. 3). Thus, evaporative effects during geotextile filtration greatly impacted the total volume reduction, VR_3*.

In all cases, the VR_3* values were smaller than those calculated by a volume balance (VR_3; eq. 7) with evaporation contributing an additional 28 to 58 L dewatered material reduction (V_{3DW} – V_{DW}*; table 5). For dairy sludge, swine sludge, and liquid dairy manure, evaporative losses based on a percentage of influent volume were 4.7%, 7.8%, and 4.9%, respectively, with the evaporation rate over the entire experiment ranging from 0.41 to 1.8 L d^{-1}. These geotextile evaporation rates were compared to the average pan evaporation rates measured within 5 km from the experimental site and corrected by 0.7 to simulate real-world applications (Linvill, 2002). With the geotextile evaporation rates being 17% to

Table 6. Dewatered material solids and plant nutrient concentrations, concentration factors (CF), and bulk manure density.

	Dairy Sludge		Swine Sludge		Liquid Dairy	
Constituent	Concentration (g L^{-1})	CF	Concentration (g L^{-1})	CF	Concentration (g L^{-1})	CF
TS[a]	299.3 (22.7)[b]	5.6	152.7 (2.81)	4.2	129.5 (3.39)	17.9
VS	90.97 (9.81)	5.4	86.3 (1.65)	4.2	96.5 (3.07)	20.5
TAN[c]	0.27 (0.065)	2.0	0.86 (0.13)	2.3	7.41 (2.14)	21.3
Org-N	3.85 (0.363)	4.9	6.67 (0.148)	4.1	4.46 (0.084)	17.0
P_2O_5	6.72 (1.46)	5.2	13.6 (0.790)	4.1	3.83 (0.682)	16.0
K_2O	0.82 (0.13)	2.8	0.96 (0.028)	2.0	0.80 (0.043)	1.6
Ca	4.47 (1.03)	5.5	8.45 (0.172)	4.2	3.01 (0.093)	13.0
Mg	0.96 (0.21)	5.0	1.27 (0.009)	4.1	0.95 (0.22)	12.8
S	1.65 (0.365)	5.0	2.36 (0.135)	4.0	0.81 (0.013)	20.5
Zn	0.05 (0.010)	1.6	0.43 (0.007)	4.0	0.05 (0.003)	24.8
Cu	0.02 (0.003)	2.8	0.06 (0.001)	4.2	0.01 (0.003)	34.2
Mn	0.16 (0.20)	9.4	0.16 (0.007)	4.1	0.03 (0.000)	17.0
Na	0.14 (0.019)	1.8	0.18 (0.003)	1.6	0.26 (0.011)	1.2
ρ_M (g L^{-1})[d]	1180.0 (20.7)		1035.3 (11.8)		969.8 (16.2)	

[a] TS and VS means, $n = 9$.
[b] Values in parentheses are standard deviations. Values shown as zero are below detection levels.
[c] Plant nutrient means, $n = 3$.
[d] Bulk manure density, $n = 9$.

61% of the average pan evaporation rates (2.29 L d^{-1} over the sludge test period and 2.95 L d^{-1} over the liquid dairy test period), water evaporation effect is further supported to be the likely cause of the TS concentration discrepancy. In full-scale operation of geotextile filtration for these materials, the bags would be fully exposed to the elements of nature where the impact of evaporation would be even greater, leading to less material requiring disposal.

When a geotextile bag is used for primary treatment and dewatered material storage of liquid dairy manure, the calculated VR_3* value of 0.036 (table 5) indicates that the 38% of solids retained would occupy only 4% of the milking center wastewater (table 5). The VR_3* values for dairy and swine lagoon sludge were very similar, with an average value of 0.186. In a practical situation, the filtrate from a geotextile bag would be directed back to the lagoon (Worley et al., 2004), and only the dewatered material would be moved off-site for land application or possible composting. While retaining up to 88% of the total solids, the volume reduction results indicate that geotextile filtration working in tandem with surface evaporation can reduce a lagoon's sludge-supernatant mixture volume by 80%. In other words, if an animal production facility currently disposing of or land applying a lagoon sludge mixture implemented on-site geotextile filtration, then the total volume of material requiring disposal is reduced to 20%. For an animal production facility, this substantial volume reduction has the added benefits of overall pumping and transportation cost reductions.

The time needed for the geotextile dewatering process was dependent on the type of material loaded. If the geotextile tube was filled with large, irregular-shaped particles, as in the case of the liquid dairy manure, then the dewatering phase was relatively rapid. For this study, the liquid dairy manure dewatered within 33 days, the fastest of the four treatments. As illustrated in figure 4, when fine-grained sludges were loaded into the bags, there was an accumulation and cake layer formation on the inside surface of the fabric. To finish all three fill-dewater cycles, both dairy and swine sludge took approximately the same 70 d time frame (table 5).

Dewatered Material Characteristics

Geotextile filtration reduced the total volume of bulk manure and, thus, concentrated the retained solids and plant nutrients (table 6). Since liquid swine exhibited gravity settling, a representative sample of dewatered material could not be obtained; thus, this treatment was excluded from table 6. When compared to the other materials, dewatered dairy sludge had both the largest solids concentration and bulk density. As to be expected from large volume reductions, the dewatered liquid dairy manure had the greatest concentrations of VS and TAN. For the remaining plant nutrients, dewatered swine sludge had the highest concentrations. The high concentration of Zn and Cu in the swine lagoon sludge was due to higher concentrations used in the rations and measured in the loaded influent (table 1).

Even though MRE values associated with constituents measured in liquid dairy manure were the lowest in this study, liquid dairy manure had the highest *CF* values (eq. 5; table 6) for all constituents except K_2O and Na. These high *CF* values are attributed to the large volume of filtrate released from the bag resulting in the small volume of dewatered solids, V_{DW}* (table 5), which trapped 34% to 67% of the solids and plant nutrients. Dairy sludge achieved greater *CF* values than swine sludge, with the *CF* value for TS of the dairy sludge 33% greater.

CONCLUSIONS

Geotextile filtration can serve an important role in animal manure management by providing an effective means to contain, dewater, and concentrate lagoon sludge and fresh animal manure. The dewatering of dairy and swine lagoon sludge and liquid dairy and swine manure was demonstrated using a hanging-bag test in which the effects of fill-dewatering cycles and manure type on mass retention efficiency were measured. The design of the hanging-bag test allowed for quantification of mass retention efficiencies of solids and plant nutrients, volume reduction, and characterization of dewatered manure.

Implementation of multiple fill-dewater cycles to increase the amount of contained material did not have statistical impact on many constituent mass retention efficiencies. For this study, there were variations in overall mass retention efficiencies among the different manures; dairy and swine lagoon sludge behaved similarly, while geotextile filtration of liquid dairy manure resulted in the lowest mass retention efficiencies. While the mass retention efficiencies for the liquid swine manure tested were adequate, the poor dewatering characteristics suggest that geotextile filtration of this oily manure was not an effective primary liquid-solid separation treatment. More favorable results may be achieved with the addition of a flocculent.

Geotextile filtration drastically reduced the overall volume of contained sludge and liquid dairy manure (less than 20% of total influent volume remained), thereby containing and concentrating the solids and making it an effective dewatering process. Use of geotextile bags represents a potentially useful tool for improvement of livestock waste management.

ACKNOWLEDGEMENTS

This work was supported with funds from USDA-ARS National Program 206: Manure and By-Product Utilization; Mirafi Division of Ten Cate Nicolon USA; South Carolina Agricultural and Forestry Research System; and Clemson University Extension. The authors would like to thank the following people for their assistance and participation: Stan Barrett, Kathryn Finnessy, Michael Nance, and David Vaughn for assisting in experimental set-up and procedures; and Drs. Jack Fowler and Roy Dodd as well as Tom Stephens for consultation on experimental applications.

REFERENCES

APHA. 2005. *Standard Methods of Examination of Water and Wastewater.* 21st ed. Washington, D.C.: American Public Health Association (APHA).

ASAE Standards. 2002. EP403.2: Design of anaerobic lagoons for animal waste management. St. Joseph, Mich.: ASAE.

Baker, K. B. 2002. Treatment of lagoon sludge and liquid animal manure utilizing geotextile filtration. MS thesis. Clemson, S.C.: Clemson University, Department of Agricultural and Biological Engineering.

Brady, N. C., and R. R. Weil. 1999. *Elements of the Nature and Properties of Soils*. 12th ed. Upper Saddle River, N.J.: Prentice Hall.

Chastain, J. P., and J. J. Camberato. 1999. Chapter 3a: Dairy manure production and nutrient content. In *Confined Animal Manure Managers Certification Program Manual: Dairy Version II*, 3a-1 – 3a-16. Clemson, S.C.: Clemson University Extension. Available at: www.clemson.edu/camm/Camm_d/Contents.htm.

Chastain, J. P., and S. Henry. 1999. Chapter 4: Management of lagoons and storage structures for swine manure. In *Confined Animal Manure Managers Certification Program Manual: Swine Version II*, 4-1 – 4-31. Clemson, S.C.: Clemson University Extension. Available at: www.clemson.edu/camm/Camm_s/Contents.htm.

Chastain, J. P., and D. E. Linvill. 1999. A model of the operating characteristics of covered lagoon digesters for swine and dairy manure. ASAE Paper No. 994045. St. Joseph, Mich.: ASAE.

Chastain, J. P., J. J. Camberato, J. E. Albrecht, and J. Adams III. 1999. Chapter 3: Swine manure production and nutrient content. In *Confined Animal Manure Managers Certification Program Manual: Swine Version II*, 3-1 – 3-18. Clemson, S.C.: Clemson University Extension. Available at: www.clemson.edu/camm/Camm_s/Contents.htm.

Chastain, J. P., W. D. Lucas, J. E. Albrecht, J. C. Pardue, J. Adams III, and K. P. Moore. 2001a. Removal of solids and major plant nutrients from swine manure using a screw press separator. *Applied Eng. in Agric*. 17(3): 355-363.

Chastain, J. P., M. B. Vanotti, and M. M. Wingfield. 2001b. Effectiveness of liquid-solid separation for treatment of flushed dairy manure: A case study. *Applied Eng. in Agric*. 17(3): 343-354.

Chastain, J. P., K. B. Cantrell, and K. P. Moore. 2005. Composition and settling characteristics of milking center wastewater: A case study. ASABE Paper No. 054102. St. Joseph, Mich.: ASABE.

DeSutter, T. M., and J. M. Ham. 2005. Lagoon-biogas emissions and carbon balance estimates of a swine production facility. *J. Environ. Qual.* 34(1): 198-206.

Fowler, J., J. C. Sprague, and D. Troups. 1994. Dredged material-filled geotextile containers. Vicksburg, Miss.: U.S. Army Engineers, Waterways Experiment Station.

Fowler, J., R. M. Bagby, and E. Trainer. 1997 Dewatering sewage sludge with geotextile tubes. *Geotech Fabrics Rep.* 15(7): 26-30.

Koerner, G. R., and R. M. Koerner. 2006. Geotextile tube assessment using a hanging bag test. *Geotext. Geomembranes* 24(2): 129-137.

Linvill, D. 2002. Professor of Agricultural Meterology, personal communication on pan evaporation rates, Department of Agricultural and Biological Engineering, Clemson University, Clemson, S.C.

Moo-Young, H. K, T. E. Myers, D. Townsend, and C. Ochola. 1999. The migration of contaminants through geosynthetic fabric containers utilized in dredging operations. *Eng. Geol.* 53(2): 167-176.

Moo-Young, H. K., D. A. Gaffney, and X. Mo. 2002. Testing procedures to assess the viability of dewatering with geotextile tubes. *Geotext. Geomembranes* 20(5): 289-303.

Mukhtar, S., J. L. Ullman, B. W. Auvermann, S. E. Feagley, and T. A. Carpenter. 2004. Impact of anaerobic lagoon management on sludge accumulation and nutrient content for dairies. *Trans. ASAE* 47(1): 251-257.

Mukhtar, S., L. A. Lazenby, and S. Rahman. 2007. Evaluation of a synthetic tube dewatering system for animal waste pollution control. *Applied Eng. in Agric*. 23(5): 669-675.

Muthukumaran, A. E., and K. Ilamparuthi. 2006. Laboratory studies on geotextile filters as used in geotextile tube dewatering. *Geotext. Geomembranes* 24(4): 210-219.

Ott, R. L., and M. Longnecker. 2001. *Statistical Methods and Data Analysis.* 5th ed. Pacific Grove, Cal.: Duxbury.

Peters, J., S. M. Combs, B. Hoskins, J. Jarman, J. Kovar, M. Watson, A. Wolf, and N. Wolf. 2003. Recommended methods of manure analysis. Publication A3769. Madison, Wisc.: University of Wisconsin Cooperative Extension. Available at: learningstore.uwex.edu/pdf/A3769.pdf.

Stone, K. C., P. G. Hunt, F. J. Humenik, and M. H. Johnson. 1998. Impact of swine waste application on ground and stream water quality in an Eastern Coastal Plain watershed. *Trans. ASAE* 41(6): 1665-1670.

Szogi, A. A., M. B. Vanotti, and A. E. Stansbery. 2006. Reduction of ammonia emissions from treated anaerobic swine lagoons. *Trans. ASABE* 49(1): 217-225.

Wilkie, A. C., H. F. Castro, K. R. Cubiniski, J. M. Owens, and S. C. Yan. 2004. Fixed-film anaerobic digestion of flushed dairy manure after primary treatment: Wastewater production and characterization. *Biosystems Eng.* 89(4): 457-471.

Worley, J. W., T. M. Bass, and P. F. Vendrell. 2004. Field test of geotextile tube for dewatering dairy lagoon sludge. ASAE Paper No. 044078. St. Joseph, Mich.: ASAE.

Zhang, R. H., and P. W. Westerman. 1997. Solid-liquid separation of animal manure for odor control and nutrient management. *Applied Eng. in Agric.* 13(5): 657-664.