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Mechanical Solid-Liquid Manure Separation: Performance Evaluation on Four New York State Dairy Farms – A Preliminary Report

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Abstract. *Five mechanical solid-liquid manure separators manufactured by three different companies and located on four production dairy farms in New York State were sampled monthly from May 2001 to December 2004 (not every separator was sampled continuously throughout this period). Samples were analyzed in an EPA approved commercial laboratory for total solids, total volatile solids, total phosphorus, ortho phosphorus, total Kjeldahl nitrogen, ammonia nitrogen, and potassium. Organic nitrogen was determined by subtraction. The efficiency of capture of each effluent stream was calculated for each constituent analyzed. All separators, regardless of farm specific affects on separation performance, captured no more than 25 percent of the nitrogen and phosphorus in the solid effluent stream. Implications on each farm's CAFO plan were analyzed and the results are presented.*

Keywords. Solid-manure separation, manure treatment, nutrient separation, separator mass flow

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INTRODUCTION

The first mechanical manure treatment process performed on dairy farms, and the one most familiar to dairy producers, was most likely solid-liquid separation of liquid dairy manure. The goals of solid-liquid separation can be singular or multiple, depending on the needs of a specific farm. In general, mechanical solid-liquid manure separators are used by dairy producers with goals to:

1. Remove a portion of the solids so liquid effluent can be more easily pumped long distances to a remote storage and/or applied to cropland
2. Reclaim a portion of the solids for use as stall bedding
3. Partition nutrients so they can be more easily land applied to far off fields or exported off-farm
4. Reduce the size of long-term storage and biological treatment lagoons

Historically, limited documentation exists relative to the quantification and success of on-farm solid-liquid separation systems. Anecdotally, it is known that removal of some manure solids results in a liquid that is more easily pumped than raw manure. Recently, the need has arisen to quantify the performance of solid-liquid manure separators so farms can evaluate:

1. A separator's impact on a comprehensive nutrient management plan (CNMP) required by Concentrated Animal Feeding Operation (CAFO) rules.
2. The quantity and quality of reclaimed manure solids so accurate economic projections can be made with respect to their end use.
3. Nutrient partitioning between separated solid and liquid effluents to determine the potential for nutrient export.

In order to address these issues, screw press separator influent and effluent samples were collected from four New York State production dairy farms once a month. Samples were analyzed by a commercial laboratory following either Environmental Protection Agency (EPA) methods or American Public Health Association Standard Methods (1992) as appropriate. Results were used to determine the in-place operating characteristics and efficiency of five solid-liquid manure separators (one farm upgraded to a newer model during the course of the study).

The goals and objectives of this paper are to:

1. Provide a brief overview of mechanical solid-liquid manure separation
2. Present manure constituent data for raw and separated effluent streams
3. Provide the percent efficiency of capture of all constituents in each effluent stream for each separator
4. Discuss anaerobic digestion and solid-liquid separation when positioned in series
5. Discuss the impact of solid-liquid separation on a nutrient management plan if solid effluent is exported

Basics of Mechanical Solid-Liquid Manure Separation

A solid-liquid manure separator, through mechanical or gravitational force, separates liquid manure into two effluent streams (Figure 1). The liquid effluent stream has less total solid (TS) content than the influent stream while the solid effluent stream has greater TS content than the influent stream. The influent stream is separated using a metal screen with several small slots (on the order of 0.03 in.). Larger dewatered solids that do not pass through the slotted screen and some of the liquid are discharged as solid effluent. Most of the liquid and some of the solids finer than the slotted screen opening pass through the screen and are discharged as liquid effluent. It should be noted that even after separation, the solid effluent stream remains rather wet, typically 70-80% moisture.

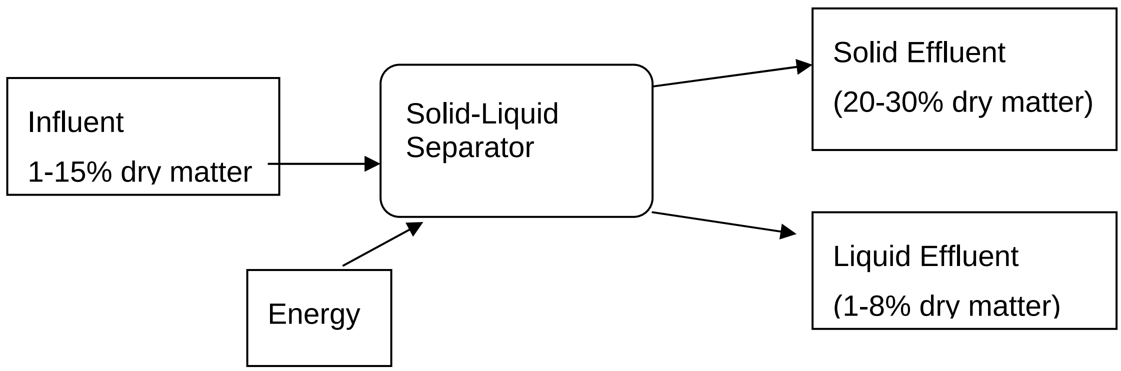

Figure 1. Flow chart for a typical mechanical solid-liquid manure separator.

LITERATURE REVIEW

Mechanical solid-liquid separation of dairy manure can be accomplished by a number of methods including a screw press separator, drag chain separator, stationary inclined screen, roller presses or vibrating screens (Hartzell, 2001). To properly size and install a solid-liquid separation system, the separator's performance characteristics must be known for the specific manure slurry found at the farm. The performance of a mechanical solid-liquid separator varies with the total solids content and the solids characteristics of the input manure. Manure slurries encountered in solid-liquid separation applications are typically between 1-15% TS. Generally mechanical screw press separator performance increases as input manure TS increases in this range (Burns and Moody, 2001). In addition to the percent TS of the manure, the type of solids also impacts separation performance (Burns and Moody, 2003). Solids separation has the potential to remove 50% of the N and P from flushed dairy manure (Chastain et al., 2001).

Farm and Mechanical Solid-Liquid Separator System Descriptions

A brief description of each of the four collaborating dairy farms that own and operate a solid-liquid manure separator is provided below. A summary of the description is shown in Table 1.

Farm AA

Farm AA is a 550-cow dairy with average milk production of 23,000 lb per cow. Over the course of the study two FAN PSS screw-press separators were positioned to process effluent from a plug-flow anaerobic digester. The first separator was a FAN model PSS 1-520 with a 0.50 mm screen opening. The second and current separator is a FAN model PSS 2-520 with a 0.50 mm screen opening. Initially reclaimed separated solids were used as freestall bedding material. After a short period of time, citing concerns for a decline in udder health and milk quality, the producer decided it would be better to compost the separated solids and sell them off-site. Composting and selling separated solids has been a moderately successful side business for the farm. Separated liquid effluent is transferred to a long-term storage and is subsequently land applied to cropland.

Farm ML

Farm ML is a 600-cow herd with a 23,000-pound rolling herd average. A Vincent screw-press separator (model KP-10 with a 2.25 mm screen opening) was installed in the manure treatment system to process anaerobic digester effluent. This farm processes the blend of manure from 505 milking cows, 95 dry cows, 178 bred heifers and imported food waste in a mixed anaerobic digester. Influent values for the separator are a variable ratio of the digested manure and food waste from ice cream, fish stick, and grape juice processing. Separated solids were used for freestall bedding for the first 12 months of separator operation. Visual observation indicated that the separated solid effluent had a finer particle size distribution compared to separated solid effluents on the other farms monitored. This may be due to a more efficient anaerobic digestion process fueled by the food waste, resulting in increased breakdown of TS. Also, separated solids were reclaimed at a slow rate due to rather low TS concentration in the separator influent. Last year, Farm ML switched back to sawdust bedding to improve the quantity of separated solids produced. Separated solid effluent is stockpiled, allowed to go through a passive heating process, and are then sold off-site or applied to cropland. Separated liquid effluent gravity flows to a long-term storage.

Farm FA

Farm FA is a 100-cow dairy herd housed in a tie stall barn with a 23,000-pound rolling herd average. A refurbished FAN screw-press separator (model PSS 2-520 with a 0.75 mm screen opening) was installed as a pre-treatment device prior to anaerobic digestion; separated liquid effluent was digested in a low hydraulic retention time anaerobic digester (Ludington, 2004, Weeks, 2002, and Wright et al., 2004). Pre-separation was a requirement based on the fixed-film design of the digester. The initial goal was to process separated solids over a 3-day period with an in-vessel composter/dryer unit for subsequent use as tie stall bedding material. However, complications with the composter/dryer precluded this from being achieved. Consequently, separated solids are applied to cropland or sold off-site.

Farm PA

Farm PA is an 800-cow dairy herd with 24,000 lbs per cow average yearly milk production. The farm uses a Houle roller separator to process raw heifer and cow manure; the farm does not currently operate an anaerobic digester, although one is under construction. Separated solid effluent is used as bedding, sold off-site, or applied to cropland. Separated liquid effluent is transferred by gravity to a long-term storage.

Table 1. Summary of key farm components for the four collaborating dairy farms.

Farm	AA	ML	FA	PA
No. of Milking Cows	550	505	100	800
Average Annual Milk Production	23,000	23,000	23,000	24,000
Separator Manufacture	FAN	Vincent	FAN	Houle
Model Type 1	PSS 1-520	KP-10	PSS 2-520	Roller Separator
Screen Size 1	0.5 mm	2.25 mm	0.75 mm	Unknown
Model Type 2	PSS 2-520	N/A	N/A	N/A
Screen Size 2	0.5 mm	N/A	N/A	N/A

MATERIALS AND METHODS

Mass flow, manure nutrient composition and concentration, and solids data from five different solid-liquid separators located on four production dairy farms was collected from May 2001 – December 2004.

Mass Flow Determination

Mass flow data for each separator was collected from the separator influent and effluents whenever possible. Solid effluent was collected in a Rubbermaid tub of known tare weight and volume. Liquid effluent was collected in a 5-gallon pail with known tare weight and volume. A stopwatch was used to time how long it took to fill the pail and tub to the top. All weights were measured using a spring scale (John Chatillon & Sons, Model IN-50 MRP). Mass and volume flow rate data was used to calculate the total material processed daily by each separator.

Operating Time Determination

The daily run time for each separator was quantified two ways. The run times were measured using a HOBO on/off sensor (Model HO6-004-02, Onset Computer Corp.) and checked regularly by producer observations.

Influent and Effluent Sampling

Monthly samples of liquid and solid effluents were taken from each separator monitored. A 5-gallon pail was used to collect liquid effluent and a Rubbermaid tub was used to collect solid effluent. Four ounce samples were taken from each collection container. The samples were immediately placed on ice and shipped to an EPA certified lab for analysis. All analysis were performed following the methods shown in Table 2 for each constituent. Samples were diluted as necessary to perform laboratory analysis.

Table 2. Test methods used for nutrients and solids.

Sampling / Monitoring Parameter	Test Method
Total Solids (TS)	EPA 160.3
Total Volatile Solids (TVS)	EPA 160.4
Total Phosphorous (Total P)	EPA 365.3
Ortho Phosphorous (Ortho P)	EPA 365.3
Total Kjeldahl Nitrogen (TKN)	EPA 351.4
Ammonia-Nitrogen (NH_3-N)	SM18 4500F
Organic Nitrogen (ON)	By subtraction
Total Potassium (Total K)	EPA SW 846 6010

DATA ANALYSIS

All data was entered into Microsoft Office EXCEL 2003. Statistics were calculated using data from all sampling events, except known outliers as determined by Cook's Distance method. All statistics calculated use the formulas found in EXCEL.

RESULTS

Data Representation

The solid-liquid manure separators monitored were adjusted at the discretion of the producer to maximize the dry matter content of the separated solid effluent. Separator influent TS concentration varies due to differences in excreted manure characteristics, barn ventilation, volume of dilution water added, presence or absence of an anaerobic digester, and inclusion of any food waste. This inherent variability of separator influent requires adjustment of the separator settings. The setting adjustments were not monitored. Data reported in the tables are average values with their corresponding 95 percent confidence interval.

Farm AA replaced the original separator (AA-1) with an updated model (AA-2) in January, 2004. In the tables that follow AA-1 represents the original separator and AA-2 represents the replacement.

Separator Mass Flow Rates

The separated liquid effluent and separated solid effluent mass flow rates are shown in Table 3. Separator installations at Farms FA and PA allowed influent flow rate to be measured directly while installation at Farms AA and ML did not; influent flow rate was calculated by performing a system mass balance where the separator liquid influent is equal to the sum of the measurements of the separator liquid and solid effluent streams.

Mass flow data for Farm FA was obtained from Ludington (2004). Superscripts a - d correspond to the sample size (n) of the chart associated with each flow rate and confidence interval.

Table 3. Average mass flow rate (lbs/min and Ft^3/min) for five solid-liquid manure separators.

Separator Influent Flow Rate					
	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
(lbs/min)	202	321	456	411[a]	750
(Ft^3/min)	3.9	6.0	7.5	6.6	12
Separated Liquid Effluent Flow Rate					
	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
(lbs/min)	172±22.4	271±54.5	454±28.4	318±100[b]	589±39.6
(Ft^3/min)	2.7±0.35	4.3±0.87	7.3±0.45	5.1±1.6	9.4±0.6
Separated Solid Effluent Flow Rate					
	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
(lbs/min)	31.8±6.8	50.0±9.67	3.35±1.09	114±11.7[c]	129±59.6
(Ft^3/min)	1.25±0.20	1.75±0.31	0.19±0.09	2.86±0.77[d]	5.21±1.70
n	27	6	4	[a]6 [b]5 [c]3 [d]4	9

The separator at Farm PA had the highest measured capacity, 750 lbs/min of separator influent producing 589 lbs/min of liquid effluent and 129 lbs/min of solid effluent. The newer FAN screw-press separator (AA-2) at Farm AA resulted in a measured increase in influent rate of 120 lbs/min, and increases in separated liquid effluent and separated solid effluent produced by 100 lbs/min and 18 lbs/min, respectively. The separator influent rates at Farms ML and FA compare closely exhibiting a 40 lbs/min difference. The separated solid production rate at Farm ML is much lower and the separated liquid rate much higher than Farm FA due to the low TS content in the separator influent at Farm ML.

The flow rate data is consistent with the FAN separator Inc. literature indicating that the PSS model separator will process 10 – 50 tons of dry solids (FAN, 2005); no unit of time was provided by the reference cited.

Vincent Corporation indicates that their KP-10 model has a capacity of 70 gallons per minute (Vincent, 2005). The measured separator influent rate at Farm ML was 54 gallons per minute.

The data also supports Houle's literature that their roller separator can process manure from up to five cows a minute (Houle, 1999). Using a manure production rate of 20.1 gallons of manure/cow-day, the calculated maximum influent rate is 100.5 gallons/minute. The data indicates that the separator at Farm PA processed 90 gallons per minute, well within is operating range.

Calculated daily values for the five solid-liquid separators are shown in Table 4. The influent volume and runtime is based on the data, 20.1 gallons of manure per cow per day and 8.34 lbs per gallon of manure (Wright et al., 1999). The effluent stream values were calculated by multiplying the runtime by the appropriate values in Table 3. The influent rate for Farm ML includes the amount of food waste imported to the farm for processing by anaerobic digestion.

Table 4. Calculated daily values for: runtime (hrs.), total volume of influent and liquid effluent (gallons) and weight of solids (tons) for five solid-liquid manure separators.

	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
Run time (hrs)	7.6	4.7	7.7	0.67	2.9
Influent (gallons)	13,300	12,700	25,500	2,010	15,600
Separated Liquid (gallons)	9,200	9,060	25,200	1,555	12,200
Separated Solids (wet-tons)	7.25	11.4	0.77	2.32	11.2

Partitioning of Solids and Nutrients

The concentration of total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_3-N), organic-nitrogen (O-N) by calculation [TKN – NH_3-N], total phosphorus as P (Total P), ortho phosphorus as P (Ortho P), total solids (TS), total volatile solids (TVS) and total potassium (Total K) were each quantified for separator influent, and separated liquid and separated solid effluent streams.

Constituents are reported on a wet-basis in pounds per 1,000 gallons for separator influent and separated liquid effluent stream (Table 5). Constituents for the separated solid effluent are reported on a wet-basis in pounds per ton (Table 6). The decision to test for total K was made later in the study, therefore the values for total K are not available for all farms. The number of samples included in the average is represented by n at the bottom of each table (n_K is the number of samples for total K).

Table 5. Average concentration of nutrients (lbs/1,000 gallons) for influent and liquid effluent streams for five mechanical solid-liquid manure separators.

Separator Influent											
Constituent		Farm AA-1		Farm AA-2		Farm ML		Farm FA		Farm PA	
TKN		43.2±2.97		36.8±7.70		26.0±1.44		33.0±1.95		34.4±5.71	
NH_3-N		23.4±1.40		18.4±1.96		10.5±1.28		18.8±1.34		16.0±1.75	
O-N		19.8±2.96		18.4±7.73		15.5±1.15		14.1±2.06		18.4±5.72	
Total P		7.45±0.60		4.39±0.47		4.67±0.51		5.42±0.54		5.59±0.40	
Ortho P		4.71±0.32		3.28±0.38		2.51±0.36		3.04±0.19		2.64±0.40	
Total K		-		18.8±3.81		21.8±4.91		-		-	
n	n_K	29	-	10	6	19	7	27	-	17	-
Separated Liquid Effluent											
Constituent		Farm AA-1		Farm AA-2		Farm ML		Farm FA		Farm PA	
TKN		38.5±3.69		34.8±7.39		24.6±1.62		32.7±2.14		33.3±3.03	
NH_3-N		22.4±2.14		19.1±3.42		9.85±1.15		18.8±1.10		15.2±1.92	
O-N		16.2±2.91		15.8±6.14		14.7±1.24		13.9±1.82		18.2±2.30	
Total P		6.49±0.49		3.98±0.51		4.53±0.45		4.98±0.37		4.85±0.52	
Ortho P		4.31±0.42		2.67±0.42		2.47±0.42		2.89±0.24		2.39±0.46	
Total K		-		17.5±2.06		20.4±4.61		-		-	
n	n_K	29	-	10	6	19	7	27	-	17	-

Table 6. Average concentration of nutrients (lbs/ton) for solid stream effluent for five mechanical solid-liquid manure separators.

Separated Solid Effluent										
Constituent		Farm AA-1		Farm AA-2		Farm ML		Farm FA		Farm PA
TKN		11.1±0.89		9.06±1.65		9.84±1.45		6.87±0.43		8.56±1.33
NH_3-N		5.16±0.33		3.92±0.47		2.35±0.34		3.29±0.28		2.75±0.39
O-N		5.91±0.88		5.14±1.53		7.50±1.34		3.46±0.31		5.80±1.43
Total P		2.28±0.23		1.64±0.33		1.86±0.26		1.12±0.12		1.05±0.13
Ortho P		1.26±0.13		0.84±0.13		0.99±0.16		0.60±0.06		0.42±0.10
Total K		-		3.70±0.25		3.59±1.03		-		-
n	n_K	29	-	10	6	19	7	27	-	17	-

Equations 1 and 2, presented by Burns and Moody (2003), can be used to quantify the efficiency of a solid-liquid manure separator. Equation 1 is used to calculate the percent of the constituents partitioned to the liquid stream. Equation 2 is used to calculate the percent of constituents partitioned to the solid stream.

$$\text{Eff. }(\%)_{Capture}\text{ liquids} = M_L(\%_{Const}) / M_{in}(\%_{Const}) \quad \text{(Equation 1)}$$

$$\text{Eff. }(\%)_{Capture}\text{ solids} = M_S(\%_{Const}) / M_{in}(\%_{Const}) \quad \text{(Equation 2)}$$

Where:

Eff. $(\%)_{Capture}$ = the separator efficiency to capture the constituents in each effluent stream

M_{in} = mass of the influent

M_L = mass of the separated liquid

M_S = mass of the separated solids

$\%_{Const}$ = the concentration of the constituent as a percent of mass of material

Equations 1 and 2 were used with data collected from the four farms. The capture efficiencies in Table 9 were derived after three steps:

1. The nutrient concentrations (Tables 5 and 6) were first converted into percents (Table 7).
2. The concentrations in percent were multiplied by the average mass flow rate data (Table 3) and constants to get pounds per hour (Table 8).
3. The efficiencies (Table 9) were calculated using equations 1 and 2 from the pounds per hour data.

The three steps are presented in detail below.

Step 1

The constituent data shown in Tables 5 and 6 was converted to a percent concentration basis and is shown in Table 7. Confidence intervals reported as 0.00 are less than 1/100 of a percent or 1/10,000.

Table 7. Average constituent concentrations (percent) for separator influent and separated liquid and solid stream effluents.

Separator Influent

Constituent	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
TKN	0.52±0.04	0.44±0.09	0.31±0.02	0.39±0.02	0.41±0.07
NH_3-N	0.28±0.02	0.22±0.02	0.13±0.02	0.23±0.02	0.19±0.02
O-N	0.24±0.04	0.22±0.09	0.19±0.01	0.17±0.02	0.22±0.07
Total P	0.09±0.01	0.05±0.01	0.06±0.01	0.06±0.01	0.07±0.00
Ortho P	0.06±0.00	0.04±0.00	0.03±0.00	0.04±0.00	0.03±0.00
TS	8.32±0.46	7.45±0.49	5.50±0.37	9.96±0.52	10.3±0.70
TVS	6.57±0.43	5.96±0.42	4.25±0.23	8.07±0.44	8.43±0.66
Total K	-	0.23±0.05	0.26±0.06	-	-
n / n_K	29 / -	10 / 6	19 / 7	27 / -	17 / -

Separated Liquid Effluent

Constituent	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
TKN	0.46±0.04	0.42±0.09	0.29±0.02	0.39±0.03	0.40±0.04
NH_3-N	0.27±0.03	0.23±0.04	0.12±0.01	0.22±0.01	0.18±0.02
O-N	0.19±0.03	0.19±0.07	0.18±0.01	0.17±0.02	0.22±0.03
Total P	0.08±0.01	0.05±0.01	0.05±0.01	0.06±0.00	0.06±0.01
Ortho P	0.05±0.00	0.03±0.01	0.03±0.00	0.03±0.00	0.03±0.01
TS	5.06±0.33	4.06±0.34	5.19±0.40	4.93±0.28	7.58±0.70
TVS	3.57±0.25	2.81±0.23	4.09±0.38	3.33±0.22	5.85±0.57
Total K	-	0.24±0.06	0.24±0.06	-	-
n / n_K	29 / -	10 / 6	19 / 7	27 / -	17 / -

Separated Solid Effluent

Constituent	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
TKN	0.55±0.04	0.45±0.08	0.49±0.07	0.34±0.02	0.43±0.07
NH_3-N	0.26±0.02	0.20±0.02	0.12±0.02	0.16±0.01	0.14±0.02
O-N	0.29±0.04	0.26±0.08	0.37±0.07	0.18±0.02	0.29±0.07
Total P	0.11±0.01	0.08±0.02	0.09±0.01	0.06±0.01	0.05±0.01
Ortho P	0.06±0.01	0.04±0.01	0.05±0.01	0.03±0.00	0.02±0.01
TS	24.6±0.67	23.7±0.88	29.3±2.48	25.3±1.12	23.9±1.16
TVS	21.9±0.67	21.3±0.92	27.4±2.38	22.1±1.07	21.9±1.06
Total K	-	0.18±0.01	0.18±0.05	-	-
n / n_K	29 / -	10 / 6	19 / 7	27 / -	17 / -

The concentration of nutrients in the influent stream is similar to the concentration of **both** the separated liquid and separated solid stream effluents for all separators. The concentrations do vary slightly from farm-to-farm. As expected, separator influent TS varied from farm to farm due to differences in excreted manure characteristics, barn ventilation, volume of dilution water addition, and the presence or absence of an anaerobic digester and inclusion of food waste. Although direct comparisons cannot be made between farms, the data suggests that compared to raw manure, TS content is reduced by anaerobic digestion, resulting in lower recovery of solids in the separation process. The liquid stream effluent from all farms with a Vincent or FAN screw-press separator had a TS content below 5.5%. The average TS content of the solid stream effluent from all separators was between 23.7 - 29.3%.

Step 2

The average constituent concentration data in Table 7 was multiplied by the average mass flow rate data in Table 3 and constants to obtain the constituent mass flow rates shown in Table 8.

Table 8. Constituent mass flow rates (lbs/hr) for five solid-liquid manure separators.

Separator Influent					
Constituent	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
TKN	62.7	84.7	85.1	97.2	185
NH_3-N	33.9	42.4	34.4	55.6	86.0
O-N	28.8	42.4	50.8	41.7	99.1
Total P	10.8	10.1	15.3	16.0	30.1
Ortho P	6.83	7.55	8.23	8.96	14.2
TS	1,010	1,430	1,500	2,455	4,650
TVS	795	1,150	1,160	1,965	3,790
Total K	-	43.4	71.3	-	-
n	29	10	19	27	17
n_K	-	6	7	-	-
Separated Liquid Effluent					
Constituent	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
TKN	47.5	67.8	80.1	74.5	141
NH_3-N	27.6	37.1	32.1	42.8	64.1
O-N	20.0	30.7	48.0	31.7	76.8
Total P	8.01	7.76	14.8	11.4	20.5
Ortho P	5.32	5.20	8.04	6.61	10.1
TS	522	660	1,410	940	2,680
TVS	368	458	1,110	634	2,070
Total K	-	34.1	66.5	-	-
n	29	10	19	27	17
n_K	-	6	7	-	-
Separated Solid Effluent					
Constituent	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
TKN	10.5	13.5	0.99	23.5	33.1
NH_3-N	4.91	5.87	0.24	11.2	10.7
O-N	5.62	7.69	0.75	12.2	22.5
Total P	2.17	2.46	0.19	3.82	4.05
Ortho P	1.20	1.26	0.10	2.04	1.64
TS	469	712	58.9	1,730	1,850
TVS	418	639	55.0	1,510	1,700
Total K	-	5.54	0.36	-	-
n	29	10	19	27	17
n_K	-	6	7	-	-

The constituent mass flow rates in Table 8 show:

- Separator AA-1 left greater mass of TS in the separated liquid stream than the separated solid stream (522 lbs/hr vs. 469 lbs/hr)
- Separator AA-2 left greater mass of TS in the separated solids stream than the separated liquid stream (712 lbs/hr vs. 660 lbs/hr)
- The separator at Farm ML left greater mass of TS in the separated liquid stream than the separated solid stream (1,410 lbs/hr vs. 58.9 lbs/hr)
- The separator at Farm FA left greater mass of TS in the separated solid stream than the separated liquid stream (1,730 lbs/hr vs. 940 lbs/hr)
- The separator at Farm PA left greater mass of TS in the separated liquid stream than the separated solid stream (2,680 lbs/hr vs. 1,850 lbs/hr)

Step 3

The percent efficiencies of capture for nutrients and solids shown in Table 9 were calculated using equations 1 and 2 with the constituent mass flow rate data shown in Table 8.

Table 9. Percent efficiency of capture for nutrients and solids for five solid-liquid manure separators.

<table>
<tr><th colspan="12">Separated Liquid Effluent</th></tr>
<tr><td colspan="2">Constituent</td><td colspan="2">Farm AA-1</td><td colspan="2">Farm AA-2</td><td colspan="2">Farm ML</td><td colspan="2">Farm FA</td><td colspan="2">Farm PA</td></tr>
<tr><td colspan="2">TKN</td><td colspan="2">75.8</td><td colspan="2">80.0</td><td colspan="2">94.0</td><td colspan="2">76.6</td><td colspan="2">76.1</td></tr>
<tr><td colspan="2">NH_3-N</td><td colspan="2">81.3</td><td colspan="2">87.5</td><td colspan="2">93.3</td><td colspan="2">77.1</td><td colspan="2">74.5</td></tr>
<tr><td colspan="2">O-N</td><td colspan="2">69.3</td><td colspan="2">72.5</td><td colspan="2">94.5</td><td colspan="2">76.0</td><td colspan="2">77.5</td></tr>
<tr><td colspan="2">Total P</td><td colspan="2">74.1</td><td colspan="2">76.7</td><td colspan="2">96.5</td><td colspan="2">71.0</td><td colspan="2">68.0</td></tr>
<tr><td colspan="2">Ortho P</td><td colspan="2">77.8</td><td colspan="2">68.9</td><td colspan="2">97.8</td><td colspan="2">73.8</td><td colspan="2">71.3</td></tr>
<tr><td colspan="2">TS</td><td colspan="2">51.8</td><td colspan="2">46.1</td><td colspan="2">93.8</td><td colspan="2">38.3</td><td colspan="2">57.6</td></tr>
<tr><td colspan="2">TVS</td><td colspan="2">46.3</td><td colspan="2">39.9</td><td colspan="2">95.6</td><td colspan="2">32.3</td><td colspan="2">54.4</td></tr>
<tr><td colspan="2">Total K</td><td colspan="2">-</td><td colspan="2">78.7</td><td colspan="2">93.2</td><td colspan="2">-</td><td colspan="2">-</td></tr>
<tr><td>n</td><td>n_K</td><td>29</td><td>-</td><td>10</td><td>6</td><td>19</td><td>7</td><td>27</td><td>-</td><td>17</td><td>-</td></tr>
<tr><th colspan="12">Separated Solid Effluent</th></tr>
<tr><td colspan="2">Constituent</td><td colspan="2">Farm AA-1</td><td colspan="2">Farm AA-2</td><td colspan="2">Farm ML</td><td colspan="2">Farm FA</td><td colspan="2">Farm PA</td></tr>
<tr><td colspan="2">TKN</td><td colspan="2">16.8</td><td colspan="2">16.0</td><td colspan="2">1.2</td><td colspan="2">24.1</td><td colspan="2">17.9</td></tr>
<tr><td colspan="2">NH_3-N</td><td colspan="2">14.5</td><td colspan="2">13.8</td><td colspan="2">0.7</td><td colspan="2">20.2</td><td colspan="2">12.4</td></tr>
<tr><td colspan="2">O-N</td><td colspan="2">19.6</td><td colspan="2">18.2</td><td colspan="2">1.5</td><td colspan="2">29.3</td><td colspan="2">22.7</td></tr>
<tr><td colspan="2">Total P</td><td colspan="2">20.1</td><td colspan="2">24.3</td><td colspan="2">1.2</td><td colspan="2">23.9</td><td colspan="2">13.4</td></tr>
<tr><td colspan="2">Ortho P</td><td colspan="2">17.5</td><td colspan="2">16.7</td><td colspan="2">1.2</td><td colspan="2">22.8</td><td colspan="2">11.6</td></tr>
<tr><td colspan="2">TS</td><td colspan="2">46.5</td><td colspan="2">49.6</td><td colspan="2">3.9</td><td colspan="2">70.5</td><td colspan="2">39.9</td></tr>
<tr><td colspan="2">TVS</td><td colspan="2">52.5</td><td colspan="2">55.7</td><td colspan="2">4.7</td><td colspan="2">76.9</td><td colspan="2">44.8</td></tr>
<tr><td colspan="2">Total K</td><td colspan="2">-</td><td colspan="2">12.7</td><td colspan="2">0.5</td><td colspan="2">-</td><td colspan="2">-</td></tr>
<tr><td>n</td><td>n_K</td><td>29</td><td>-</td><td>10</td><td>6</td><td>19</td><td>7</td><td>27</td><td>-</td><td>17</td><td>-</td></tr>
</table>

The efficiencies in Table 9 indicate that all separators, regardless of farm specific affects on separator performance, capture no more than 25 percent of the nitrogen and phosphorus in the solid stream effluent.

The FAN separator at Farm FA had the highest TS capture efficiency in the solid stream effluent with 70.5 percent. This is likely a combination of a good overall separator design and installation as well as a function of higher TS content of separator influent. Farm ML had the lowest TS reclamation efficiency at 3.9 percent; this may be explained by the low TS concentration in the separator influent, and may not reflect on the overall design, installation, or maintenance of the separator. The Houle roller separator was 7 percent less efficient in reclaiming TS in the solids stream of the effluent than the least efficient FAN screw-press separator.

The majority of the mass balances close within 10 percent as shown in Table 10 and is considered acceptable. To calculate mass balance closure, the efficiency from the separated liquid stream was added to the efficiency from the separated solid stream to get the total separator efficiency. When a mass balance closes, there is no loss of mass between the influent stream and the sum of the effluent streams for a system. The difference or "error" can be attributed to variability in the lab results, field measurements, and properties of the manure materials themselves.

Table 10. Mass balance closure for five solid-liquid manure separators.

<table>
<tr><td colspan="2">Constituent</td><td colspan="2">Farm AA-1</td><td colspan="2">Farm AA-2</td><td colspan="2">Farm ML</td><td colspan="2">Farm FA</td><td colspan="2">Farm PA</td></tr>
<tr><td colspan="2">TKN</td><td colspan="2">92.6</td><td colspan="2">96.0</td><td colspan="2">95.2</td><td colspan="2">100</td><td colspan="2">94.0</td></tr>
<tr><td colspan="2">NH_3-N</td><td colspan="2">95.7</td><td colspan="2">101</td><td colspan="2">94.0</td><td colspan="2">97.3</td><td colspan="2">86.9</td></tr>
<tr><td colspan="2">O-N</td><td colspan="2">88.9</td><td colspan="2">90.6</td><td colspan="2">96.0</td><td colspan="2">105</td><td colspan="2">100</td></tr>
<tr><td colspan="2">Total P</td><td colspan="2">94.2</td><td colspan="2">100</td><td colspan="2">97.7</td><td colspan="2">94.9</td><td colspan="2">81.5</td></tr>
<tr><td colspan="2">Ortho P</td><td colspan="2">95.4</td><td colspan="2">85.5</td><td colspan="2">99.0</td><td colspan="2">96.6</td><td colspan="2">82.9</td></tr>
<tr><td colspan="2">TS</td><td colspan="2">98.3</td><td colspan="2">95.7</td><td colspan="2">97.7</td><td colspan="2">108</td><td colspan="2">97.5</td></tr>
<tr><td colspan="2">TVS</td><td colspan="2">98.8</td><td colspan="2">95.6</td><td colspan="2">100</td><td colspan="2">109</td><td colspan="2">99.2</td></tr>
<tr><td colspan="2">Total K</td><td colspan="2">-</td><td colspan="2">91.4</td><td colspan="2">93.7</td><td colspan="2">-</td><td colspan="2">-</td></tr>
<tr><td>n</td><td>n_K</td><td>29</td><td>-</td><td>10</td><td>6</td><td>19</td><td>7</td><td>27</td><td>-</td><td>17</td><td>-</td></tr>
</table>

Mechanical Solid-Liquid Separation and Anaerobic Digestion

The solid-liquid manure separators at Farms AA and ML were positioned to separate anaerobic digester effluent. The bacterium in an anaerobic digester converts a portion of the biologically digestible solids into biogas. Therefore, separation post digestion may result in fewer daily solids reclaimed depending on the particle size consumed by the digester microbes. For comparison, 712 lbs/hr were reclaimed at Farm AA versus 1,730 lbs/hr at Farm FA as shown in Table 4. Conversely, by separating pre-digestion Farm FA looses biologically available solids to the solid stream effluent. This may reduce total biogas production at Farm FA. A farm with an anaerobic digester needs to weigh these effects carefully before installing a solid-liquid manure separator. If the goal is to separate more solids and/or the associated nutrients for use as bedding or export, more solids may be extracted pre-digestion.

Potential Impact of Nutrient Partitioning on CAFO Plans

The various performance measurements of the five manure separation systems allow for an estimated comparison of volume of influent before separation and the separated liquid and solid fractions after separation. These estimations are important to evaluate the potential for a solid-liquid manure separator to partition nutrients and mass and to understand the potential impact on the farm's nutrient management plan and manure nutrient balance. As indicated above, across all farms, there is surprisingly little difference between the nutrient concentration of the separator influent, the separated liquid effluent and the separated solid effluents. The difference between liquid influent and separated liquid effluent is that the separated liquid is lower in TS, not in nutrient concentrations. Consequently, when balancing field crop application for nitrogen, the influent and the separated liquid effluent would be applied at virtually identical rates.

Where is the advantage of mechanical separation if the nutrient concentration is the same before and after separation? In some cases, there was a substantial reduction in the total volume of separated liquid effluent as compared to the separator influent. For example, as shown in Table 11, for Farm AA-2, there are 1.3 million gallons **less** separated liquid effluent than separator influent, or a reduction of 29 percent in total annual volume that must be handled, resulting in a substantial reduction in wet storage requirement. This also means a reduction in acreage needed to balance for nitrogen under current CAFO requirements **if** a meaningful percentage of the separated solids are exported.

Table 11. Estimated annual volume of influent and separated liquids and weight of separated solids and volume of liquid reduction due to separation.

	Farm AA-1	Farm AA-2	Farm ML	Farm FA	Farm PA
Influent (gallons/year)	4,854,500	4,635,500	9,307,500	733,650	5,694,000
Separated Liquid (gallons/year)	3,358,000	3,306,900	9,198,000	567,575	4,453,000
Separated Solids (wet tons/year)	2,646	4,161	281	846	4,088
Influent minus separated liquid (gallons/year)	1,496,500	1,328,600	109,500	166,075	1,241,000
Percent reduction of separated liquid vs. influent	31	29	1.1	22	22

In order to allow for a direct comparison between farms, the calculations below are based on applying all manure by Spring incorporation to third and fourth year cornfields to achieve a net of 120 pounds of nitrogen per acre. (This would require manure application at a rate of approximately 216 pounds of N per acre, of which approximately 120 pounds of N is expected to be utilized by the crop. An additional 30 pounds of inorganic nitrogen is assumed to be applied as starter fertilizer.)

Based on the concentrations in Table 5, Farm AA-2 will need to apply 6,000 gallons/acre of either the influent or separated liquid. But since the separated liquid volume is reduced by 1.3 million gallons by separation at Farm AA-2 the N-based application rate of 120 pounds net nitrogen requires only 551 acres to accept the total separated liquid effluent versus 772 acres if the total influent were directly field spread – a reduction of 29 percent.

An analysis of Farm FA and Farm PA reveal similar results, keeping the same target N rate as for Farm AA-2 example above, both farms need to apply 6,300 gallons/acre Spring incorporated. Consequently, Farm FA requires 24 less acres, or about 22 percent less land, and Farm PA requires about 197 fewer acres, or about 22 percent less land. Though nutrient partitioning is somewhat lower for Farms FA and PA as compared to Farm AA-2, the nutrient export potential and impact on acreage is substantial. Applying the same analysis to Farm ML, 90 fewer acres or about 8 percent less land is needed for application of the separator influent versus the separated liquid, a considerably smaller difference compared to the other farms studied.

In four of the five separators analyzed, significant amounts of solids were separated from the raw manure separator influent, potentially allowing for 16-25 percent of the nitrogen and 13-25 percent of the phosphorus in the separator influent to be exported. In each of these cases, the TS content of the separator influent was at least 7.45 percent and up to 10.3 percent. However, Farm ML exhibits a very different result than the other operations. Farm ML is estimated to generate 5.5 million gallons of manure per year. In addition, the producer estimates importing 3.8 million gallons annually of processed food waste; the food waste is low TS and of varying nutrient content. Food waste is mixed with dairy manure pre-digestion. The food waste increases the separator influent volume by 69 percent and reduces the TS content of the separator influent as compared to other farms in the analysis. The TS content of Farm ML's separator influent (5.5 percent) was much lower than the other farms, and this seemed to have a dramatic impact on the capture of solids and therefore nutrients. Approximately 2 percent of the total N and P were captured in the separated solids.

Although this dataset is too small to draw sweeping conclusions, the data suggests that farms with a low TS separator influent, due to significant dilution by other liquids, **may not** capture significant amounts of solids or nutrients through mechanical solid-liquid separation post digestion. Consequently, if a certified nutrient management plan (CNMP) depends on nutrient export, the farm may consider separating pre-digestion, or possibly additional treatment may be necessary to capture more nutrients if significant liquids are added to the separator influent. This could be the case where the separator influent receives substantial amounts of water from some combination of rainfall and storm runoff or milking center wastewater, or where waste milk or other food waste products are received. At this time, chemical capture of phosphorus is reasonably well understood and could be accomplished post mechanical solid-liquid separation. Currently, nitrogen is often the limiting factor in most dairy nutrient management plans. Additional research is necessary to determine how to manage nitrogen in this context.

Also, a disadvantage of separating and exporting nutrients via separated solids is that an important soil amendment is exported as well. The separated solids contain organic matter and carbon that play an important role in soil quality. Maintaining soil health and structure may require practices such as planting cover crops and reducing tillage where possible on operations that choose to export nutrients by selling separated solids.

CONCLUSIONS

Based on the data analyzed, the following conclusions can be made.

- Across all farms there is surprisingly little difference between the nutrient concentration of the separator influent, the separated liquid effluent or the separated solid effluent.
- The volume of a liquid storage could be reduced by 1.1 – 31 percent (109,500 - 1,496,500 gallons) by using a mechanical solid-liquid manure separator, with 4 out of the 5 systems delivering a 22-30% reduction. This also means a reduction in acreage needed to balance for nitrogen under current CAFO requirements **if** a significant portion of the separated solids are exported.
- The separated liquid stream has substantially more nutrients by mass than the separated solid stream, regardless of separator manufacturer or farm. Therefore, as a general rule, the data supports that the nutrients follow the mass, and the mass is with the separated liquid effluent.
- On the four farms (five separators) the highest solid efficiency capture rate was 70.5 percent the lowest was 3.9 percent. If Farm ML is disregarded due to low influent TS the lower range of capture increases in 40 percent for Farm PA.
- Exporting separated solids also means exporting organic mater and carbon that play an important part in soil quality.
- No more than 25 percent of the nitrogen and phosphorus were partitioned to the solid effluent stream.
- The same solid-liquid manure separator may not perform as well on one farm as it does on another.
- The same solid-liquid manure separator may not perform the same way every day.

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