Effect of Solid Separation on Mitigation of Methane Emission in Dairy Manure Lagoons

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Project objectives
Objective 1. Determine the effect of existing solid separation technologies on the reduction of methane emissions from flushed dairy manure.
Objective 2. Analyze the costs and benefits of various solid-liquid separation technologies and develop recommendations for selecting, applying and improving the solid-liquid separation technologies for achieving different levels of methane emission reductions.

Abstract
The dairy industry represents California's largest agricultural commodity, generating $6.56 billion dollars out of a total $50 billion in agricultural production. California dairies are also large sources of greenhouse gas (GHG) emissions. Manure flushing and lagoon storage are common manure management practices on dairies. Solid-liquid separation technologies have the abilities to reduce methane emissions from lagoons by reducing the amount of volatile solids loaded into lagoons. The goal of this study was to quantify the potential reduction of methane emissions from lagoons by using various solid-liquid separation technologies and to determine the cost implications for deploying these separation technologies on dairies.

Four mechanical (screen) separators, one weeping wall, and one advanced multistage separation technology were studied across various seasons on six dairies. The performance of these separators was assessed with respect to total and volatile solids (TS and VS) removal efficiencies and methane potential reduction for flushed manure prior to lagoon storage. The first five separators were evaluated for two to four seasons during 2017-2018. Two cells of the weeping wall system were evaluated during the fall of 2018. The results of this study are summarized as follows:

Parameter	Single-stage horizontal scraped screen separator	Single-stage sloped single-screen separator	Single-stage sloped dual-screen separator	Two-stage sloped dual-screen separator	Advanced multistage separator system	Weeping wall
TS removal efficiency (%)	4.7-8.0	20.1-38.4	27.7-48.9	37.6-60.2	64.2-78.8	78.4-81.9
VS removal efficiency (%)	6.5-12.1	26.4-48.8	35.5-58.4	41.4-72.8	62.7-79.6	79.0-86.1
CH_4 potential reduction (%)	1.4-8.4	28.9-42.2	38.2-57.2	28.2-73.1	69.0-83.4	75.4-80.6
Annualized cost ($/head/ year)	40.17	26.33	42.43	44.88	73.41	29.99

The performance of the mechanical screen separators depended on manure characteristics, system design (e.g., screen size and orientation), separator operation and management (manure flow rate), and manure processing pit type and configuration. The economics of these separators was analyzed. Although the single-stage sloped single-screen separator had a lowest annualized cost per milking cow, it had low solids removal efficiencies and methane potential reduction. The two-stage sloped dual-screen separator showed a better performance with slightly higher annualized cost per milking cow than the single stage sloped dual-screen separator from the same manufacturer. The advanced multistage separator system achieved high solids removals and methane potential reduction. However, it had the highest annualized capital cost per cow among all the studied systems. The weeping wall system achieved the highest solids removals and methane potential reduction with a relatively low annualized cost per cow. However, this system may have methane emissions during the filling and storage time of cells, which were not measured. Recommendations are provided for future research to address the uncertainties and questions uncovered through the course of this study.

Introduction

Separating and removing solids from dairy manure reduces the organic loading to lagoons and can therefore mitigate emissions of methane and other gases produced in anaerobic conditions. Several technologies are currently used on dairies in California. The efficiency of a certain separation technology depends on manure characteristics, equipment or system design and configuration, and operational parameters. Table 1 shows the solids removal efficiency of several screen separators for dairy manure as reported in the literature.

Table 1.A comparison of selected screen separators for dairy manure

Type of separator	Screen size (mm)	Flow rate (m^3/min)	TS of inflow (%)	Dry matter removal (%)	Reference
Rotary screen	0.75	0.41-0.75	0.52	5	Hegg et al., (1981)[1]
		0.45-0.97	0.81	10	
		0.78-0.91	1.14	4	
		0.08-0.34	2.95	14	
Sloped screen				67	Graves et al. (1971)
Inclined stationary Screen	1.5		3.83	60.9 (62.8*)	Chastain et al. (2001)[1]

1: calculated based on the difference in the concentration

*: Reduction of volatile solids

A literature review on methane production potential from dairy manure that looked at both flush manure and solid separation treatments, to varying degrees, showed that methane potential from manure after some solids are removed ranged from 60% to 85% of that for untreated manure (Table 2). This indicates 15% to 40% methane potential reduction. Screens and presses were used for solid separation in these studies.

Table 2. Relative methane production potential from solids-separated dairy manure compared to untreated manure

Separation Method	Relative methane potential (treated / raw manure, %)		Reference
	Filtrate (after solids separation)	% of initial VS in Filtrate	
Screening	85%	54%	Hills (1985)
Screening	72%	62%	El-Mashad and Zhang (2010)
Screening	60%	48.7%	Rico (2007)
Screw Press	70%	~30%	Witarsa (2015)
Roller Press	70%	~50%	Pain et al. (1984)
Screw Press	63%	~50%	Amon et al. (2006)

Hills (1985) investigated and compared the methane production potential of untreated and filtered dairy manure (with 10 mesh screen), using 4 L laboratory digesters operated continuously at

35° C for 100 days. Their results showed that solid separation by screening reduced the methane production potential by 15%. El-Mashad and Zhang (2010) screened manure using a screen with 2-mm openings and conducted assays of the untreated manure and the coarse and fine fractions of the removed solids using 1 L laboratory batch digesters operated at 35°C for 30 days. Their results showed 28% reduction in methane production potential of the manure after filtration. Rico (2007) looked at the methane production potentials of solid and liquid dairy manure fractions. Manure at 8% solids was collected followed by screening of a portion of the manure with a screen with 1-mm openings. The methane production potential for raw and screened manure (filtrate) was determined using 2.5 L batch laboratory reactors operated at 35°C for 45 days. Their results showed that the screened manure produced about 40% less methane than the untreated manure. Witarsa (2015) investigated methane production potential of flush manure and solid separation treated dairy manure under psychrophilic digestion conditions (< 25°C). Manure was collected before and after a screw press that removed about 70% of the total solids. Methane potential was determined in 250 ml reactors held at 24°C. Methane production potential from the filtrate was about 30% less than the raw manure. Pain et al. (1984) operated two 125 m^3 mixed tank mesophilic digesters at a dairy with one fed with 7% TS dairy manure slurry and the other digester used the filtrate (4% TS) from roller press screen separator. They found that the methane production from the filtrate was about 30% less than the raw manure. Amon et al. (2006) measured GHG emissions from different treatments of stored-then-land-applied dairy slurry manure (untreated slurry, liquid and solids fraction separation w/ screw-sieve, digestate from slurry digester, slurry w/ straw cover and aerated slurry[1]). Approximately 10 m^3 of each treatment type was stored in a concrete in-ground tank with a loose wooden cover for 80 days (mean slurry temperature was 17°C) and then land-applied. Relative GHG emissions (for storage and land application combined) of the separated and aerated slurry treatments were 63% and 58%, respectively, of that from the untreated slurry.

As discussed above, previous studies have shown that solid separation of dairy manure could result in a significant reduction in the methane production potential of the manure. However, most of these studies were conducted many years ago, were lab scale studies, did not investigate on-dairy separators or manure conditions thoroughly, and were not under California conditions or on dairies under actual management conditions. Moreover, most of the published studies calculated the separator efficiency using the difference between the concentrations of the inlet and outlet of the separators, which neglects differences in flow rate caused by the removal of solids. There is a need to evaluate the efficiencies of the manure separators using a mass balance approach. The mass balance approach is reliable because it takes into consideration the total amount of solids removed from a certain amount of manure inlet to a separator. It could help in accurately determine the amount of TS and VS that can be diverted from manure lagoons.

The goal of this research was to quantify how much methane emissions from flushed manure can potentially be reduced by using different solid-liquid separation technologies and to determine the cost implications for deploying these separation technologies on dairies. The results will be useful for developing technological recommendations for reducing methane emissions in lagoons.

The specific objectives were to:

1. Determine the effect of existing solid-liquid separation technologies on methane emission potential of flushed dairy manure.

2. Analyze the costs and benefits of various solid-liquid separation technologies and develop recommendations for selecting, applying and improving the solid-liquid separation technologies for achieving different levels of methane emission reductions.

Work Description

Objective 1. Determine the effect of existing solid separation technologies on methane emission potential of flushed dairy manure.

Task 1.1. Selecting solid separators, developing sampling and test plans, and setting up laboratory experiments

Number of sites, separator technologies, and sampling frequency

The initial proposal called for the selection of ten separators to represent five different types of solid separation technologies: stationary screen, vibrating screen, screw press, settling basin, and weeping wall. Meetings in February and May 2017 between the UC Davis project team, project managers from the California Department of Food and Agriculture (CDFA), and dairy industry consultants identified several multistage separators in use on dairies, offering the opportunity to gather additional data on performance and cost-benefit analysis from single sites. In light of this development, it was agreed that a reduction to six sites would be acceptable while still addressing project goals.

The project team selected four dairies with different types of mechanical solid-liquid separations systems (Dairies A, B, D, and F) representative of technologies found in California. A fifth dairy was selected based on its unique advanced multistage solid-liquid separation technology (Dairy C). The sixth and final dairy was chosen to study weeping walls (Dairy E).

Dairies with mechanical solid-liquid separation systems were studied four times, once each season, when possible. The weeping wall, due to its complexity and the additional time required to study the system, was studied twice. Dates of each dairy sampling are provided in the results section under each dairy.

Selection of dairy sites

Beginning April 2017, the project team visited dairies throughout the state to identify sites for inclusion in the study. The dairy owners and managers provided the project team with a tour and comprehensive description of each dairy's operation and separator system. The project team, in return, described sampling plans and identified work necessary to prepare each site for sampling. Specifically, the team identified separator retrofits required to allow sampling from the separator's inlet and outlet flow streams, and to install the project team's flow meter. Final site selections were made based on dairymen's willingness to participate and site suitability.

Dairies A through F were identified and selected by October 2017. In October 2017, after complications with sampling at the first Dairy D site, henceforth referred to as Dairy D*, the project team coordinated with an outside contractor to make further modifications to the site. The project team returned to the dairy in December to observe site modifications when significant deposit buildup in the dairy's plumbing was discovered. These deposits made flow measurement, and therefore determination of separator efficiency and methane potential reduction infeasible. An alternative Dairy D was identified and selected in December 2017, concluding site selection. The final list of six dairies by Dairy ID and technology are identified in Table 3. Table 4 shows the month each site selection was finalized.

Table 3. Dairy by site ID and separator technology

Technology	Dairy	Separator Description
1	A	1-stage sloped dual-screen
1	B	2-stage sloped dual-screen
2	C	Advanced multistage system
3	D*	2-stage horizontal scraped-screen
3	D	1-stage horizontal scraped-screen
4	E	Weeping wall
5	F	1-stage sloped single-screen

*first dairy D with sampling complications

Table 4. Site selection timeline

	2017 (Month)						
Site ID	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Dairy A	X						
Dairy B		X					
Dairy C		X					
Dairy D*				X			
Dairy D							X
Dairy E				X			
Dairy F					X		

Description of the separator systems

The studied technologies on the selected dairies and the screen specifications are shown in Table 5.

Table 5. Dairy, separator technology, and separator screen size

Dairy	Separator Technology	Screen Size	
		1st Stage	**2nd Stage**
A	1-stage sloped dual-screen	**Type:** Hybrid, slit Top 2/3: 0.020 in. (508 µm) Bottom 1/3: 0.025 in. (635 µm)	NA
B	2-stage sloped dual-screen	**Type:** Hybrid, slit Top 2/3: 0.020 in. (508 µm) Bottom 1/3: 0.025 in. (635 µm)	**Type:** Hybrid, slit Top 2/3: 0.010 in. (254 µm) Bottom 1/3: 0.015 in. (381 µm)
C	Advanced multistage system	**Separation zone:** Round hole 0.125 in. (3,175 µm) **Dewatering zone:** Round hole 0.125 in. (3,175 µm)	**Separation zone:** Square hole #30 mesh or 0.021 in. (533 µm) **Dewatering zone:** Round hole 0.125 in. (3,175 µm)
D*	**(Replaced)** 2-stage horizontal scraped screen	**Type:** Round hole 18-gauge, 0.094 in. (2,380 µm)	**Type:** Round hole 22 gauge or 0.05 in. (1,270 µm)
D	1-stage horizontal scraped screen	**Type:** Round hole 18-gauge, 0.094 in. (2,380 µm)	NA
E	Weeping wall	**Types:** Slit An inch to several inches	NA
F	1-stage sloped single-screen	**Type:** Hybrid, slit Top 1/3: 0.015 in. (381 µm) Middle 1/3: 0.025 in. (635 µm) Bottom 1/3: 0.035 in. (889 µm)	NA

Separator systems on Dairies A and B

Dairy A and B employ sloped dual-screen separators made by the same manufacturer. The screens are slit type. The top two-thirds of the screen has a smaller screen size than the bottom one-third. Dairy A is a single stage system with a screen size of 508 µm along the top two-thirds and 635 µm along the bottom one-third of the screen. Dairy B is a 2-stage system with coarse and fine separators. Dairy B's first stage is identical to Dairy A's separator. Dairy B's second stage has an opening of 254 µm along the top two-thirds and 381 µm along the bottom one-third of the screen.

Figure 1 shows pictures of the 1-stage sloped dual-screen separator at Dairy A as well as a close-up view of the separator screen. In the right picture, the separator has turned off and solids remain on the screen. The cross bar above the screen at the top of the image has misters, which continuously supply the screen with water.

Figure 1. Dairy A: (Left) 1-stage sloped dual-screen separator, and (Right) closer view of the type of separator screen on Dairy's A and B

Figure 2 is a picture of the 2-stage sloped dual-screen system at Dairy B. This separator is manufactured by the same company as the separator on Dairy A. The separator on the right side of the picture, is the 1st stage, or coarse separator while the one on the left is the 2nd stage, or fine separator. The 1st stage is identical to Dairy A's separator.

Figure 2. Dairy B: 2-stage sloped dual-screen separator as seen from the processing pit

Separation system on Dairy C

Dairy C is an advanced multistage separator system that employs rotary drum mechanical separators. Dairy C has two stages of rotary drum separators, a coarse and fine stage. The drum in the coarse stage has round holes 3,175 µm in diameter. The rotary drum in the fine separator has square holes 533 µm in size. Both stages have a roller press at the end of each separator that dewaters separated solids against a screen. This perforated dewatering screen has round holes 3,175 µm in diameter. Figure 3 shows an aerial view of the multistage separator system at Dairy C, as seen from a drone. On the right is the system's settling tank. The tall cylindrical black tanks just to the left of the settling tank are a sand trap and buffer tank, which reside in between the reception pit and 1st stage and settling tank and 2nd stage separators, respectively. To the left of the cylindrical tanks are 5 rotary drum separators. The first two on the left are the 1st stage, coarse separators, while the next three over are the 2nd stage, fine separators. Solids land underneath the separators. A small reception pit (Figure 3, top right) and the earthen settling basin (Figure 3, top left) can be seen in the background.

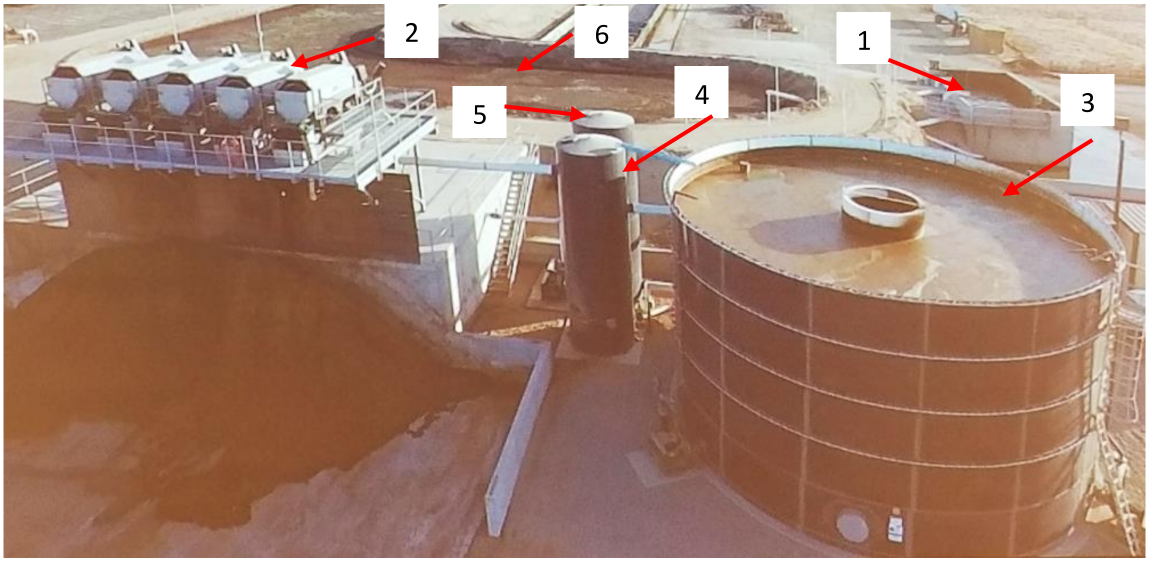

Figure 3. Dairy C: Overhead view of the advanced multistage separator system:1, reception pit; 2, rotary drum mechanical separator; 3, settling tank; 4, buffer tank; 5, sand trap; and 6, settling basin

Separation system on dairy D

Dairies D* and D have horizontal scraped screen-type separators. Dairy D* is a 2-stage system. Both separator screens are perforated with round holes. The first stage is for coarse screening and was originally designed with a hybrid screen. The first meter was originally designed with a fine screen with 22-gauge holes (1,270 µm) while the remaining length was a coarse 18 gauge screen (2,380 µm). In practice, the fine screen is less durable than the coarse one. Contact between the fine screen and the separator's metal paddles wears them down more quickly than the coarse screen, requiring more frequent replacement. For this reason, the company servicing this separator has opted to replace the fine screen with the coarse screen. Dairy D's separator is identical to Dairy D*'s first stage separator. Dairy D*'s second stage is a uniform fine screen with 22-gauge holes (1,270 µm). Figure 4 shows pictures of Dairy D's 1-stage horizontal scraped-screen separator. The left image is a picture of the separator from the ground while the right image is a photo from the top of the separator. It shows the separator's paddles conveying manure solids across the screen.

Figure 4. Dairy D: **(Left)** horizontal scraped-screen separator as seen from the ground and **(Right)** close up view of separator paddles and screen

Separation system on Dairy E

The screen lining the walls of Dairy E's weeping walls are slit type with openings ranging from one to several inches. Figure 5 and 6 are photos of the weeping wall at Dairy E. Figure 5 shows two adjacent cells of the weeping wall. The left cell had just been emptied while the right cell continues to be supplied with flush manure and filled. Birds can be seen on top of the filling cell, feeding on undigested grains in the manure. Figure 6 is a photo of the side of the weeping wall as it is weeping flush manure. The weeping wall receives flush manure, which must travel through the solids to empty out the side and into the lane. The exiting flush manure travels down lanes in between the cells of the weeping wall where it collects at a drain and flows into the lagoon.

Figure 5. Dairy E: Weeping wall, a view of 2 adjacent cells
The left cell is empty while the right cell is filling

Figure 6. Dairy E: Weeping wall weeping during a cell filling

Separation system on Dairy F

Dairy F employs a sloped single-screen separator made by a different manufacturer than Dairies A and B. The screen on Dairy F's separator is also slit type. The screen is split into three sections. The top one-third of the screen is fine with 381 µm openings, the middle third has 635 µm openings, and the bottom third has 889 µm openings. Dairy F's 1-stage sloped single-screen separator system is shown in Figure 7. The photo on the left is a side view of the separator from the ground. The picture on the right shows the separator's screen. A large roller press, spanning the width of the separator, is located at the base of the screen and dewaters separated solids.

Figure 7. Dairy F: 1-stage sloped single-screen separator

Sampling and testing plans

Evaluating each system consisted of sampling the separator inlet and outlet flow streams at regular intervals, measuring the total flow passing through the separator, weighing the separated solids onsite, and collecting a solids sample. The samples were taken back to the Bioenvironmental Engineering (BEE) Lab at UC Davis for analysis of total and volatile solids concentrations, flow data, and biomethane potential. The data was then used to determine each separator's total and volatile solids removal efficiencies and methane potential reduction from the storage lagoon.

The mechanical separator systems, Dairies A-D and F, were evaluated for up to 24 hours, once each season: summer, fall, winter, and spring. The weeping wall system, Dairy E, was evaluated over the course of the filling of two weeping wall cells, each lasting about 2 weeks.

Field measurements included: the flow rate of inlet manure, the weight of separated manure solids, and the separator inlet and outlet manure samples collected at regular intervals over the course of the sampling period.

Figure 8 shows a manure management system diagram representative of the dairies in this study. Flow 1 in Figure 8 shows potential sources of the flush water, which includes some or all of the following: the anaerobic storage lagoon (flow 1a), typically pumped from the top of the lagoon, milking parlor water (flow 1b), fresh water from the well (flow 1c), and/or recycled water from the flush manure collection pit (flow 1d), depending on each dairy's manure management plan. Flush water enters the animal pens where it picks up and conveys manure through the graded lanes and gravity flows into a sand trap (unit operation 2). Sand and larger manure particles settle out in the sand trap, which is cleaned out regularly based on the specific dairy's operation and dried for use as bedding. The flush water flows into a manure collection pit with pumps and/or agitators. Collection pits (unit operation 3) vary in construction materials and size. Simple pits may be earthen, dirt lined, while more advanced, costly ones are constructed out of concrete. The most basic are small, equipped with one pump, serving only as reception pits to collect flush water for transfer to the separator. Other, more advanced pits are large, hexagonal processing pits, with several agitators and pumps, designed to provide a homogeneous influent for the separators, as well as some buffer capacity for the flush system. The pumps and agitators are controlled by level sensors. Once the water level in the processing pit gets to a predetermined point, the agitator pump will start and mix the solids in the pit. Then the separator pump will turn on and pump the flush water to the separator (flow 4). Separated solids (flow B) drop onto a concrete pad and are usually dried for land application or bedding. Bedding (flow E) is composed of a mixture of some or all of the following materials, mixed and subjected to either composting or advanced solar drying: sand (flow A), separated solids (flow B), nut shells and/or other material from off the dairy (flow C), and excavated lagoon and/or settling pond solids (flow D). Many dairies employ a settling basin, which receives screened flush water from the separator (flow 5) for further separation, while on other dairies, flush water proceeds directly in the storage lagoon (flow 6).

Methods for on-dairy sampling work
Flow measurement

Flow rate and total flow were measured at the separator inlet using a MACE™ Agriflow XCi data logger and controller measuring from a MACE™ doppler flow sensor. The doppler ultrasonic insert velocity sensor was inserted by way of a saddle and nipple into full pipes for flow determination, except at the site of the weeping wall wherein a MACE™ doppler ultrasonic area/velocity sensor was used to measure the flow in a partially full pipe. The flow meter measured and logged data every 30-120 seconds. Velocity data was converted to flow rate by multiplying the velocity by the inner diameter of the pipe, in the case of full pipes. In the case of partially full pipes, an added depth sensor allowed the system to calculate the cross-sectional area of flush flow in the pipe, which when multiplied by the velocity, provided the flow rate. Once installed, the flowmeter measured flow continuously until the end of the sampling event.

Sampling period, and liquid sample collection and handling

The sampling period varied between 6 and 24 hours for mechanical separators and between 8 and 48 hours for the weeping wall. For 24 hour or greater sampling, work was split into multiple shifts, with teams of 1-2 people covering a 12hour shift.

Liquid samples from the inlet and outlet of mechanical separators were collected every 5-30 minutes, depending on the dairy and sampling event. Liquid inlet and outlet samples were collected every 1.5-2 hours for the weeping wall due to the comparatively long filling time of two weeks for the system. To minimize the error in sampling, when it was easy to reach the inlet and outlet of the separators, representative samples from the liquid streams were collected in 5-gallon buckets that were then swirled and finally approximately 450 ml of the liquid was collected in plastic bottles with a volume of 500 ml. When it was difficult to reach the inlet or outlet of the separators, a small bottle with a volume of 100 ml was attached to a long stick to collect (i.e., in several times) the 450 ml representative samples. Collected samples were immediately placed in a cooler and kept on ice until transferred to a refrigerator or freezer back at the BEE lab at UC Davis.

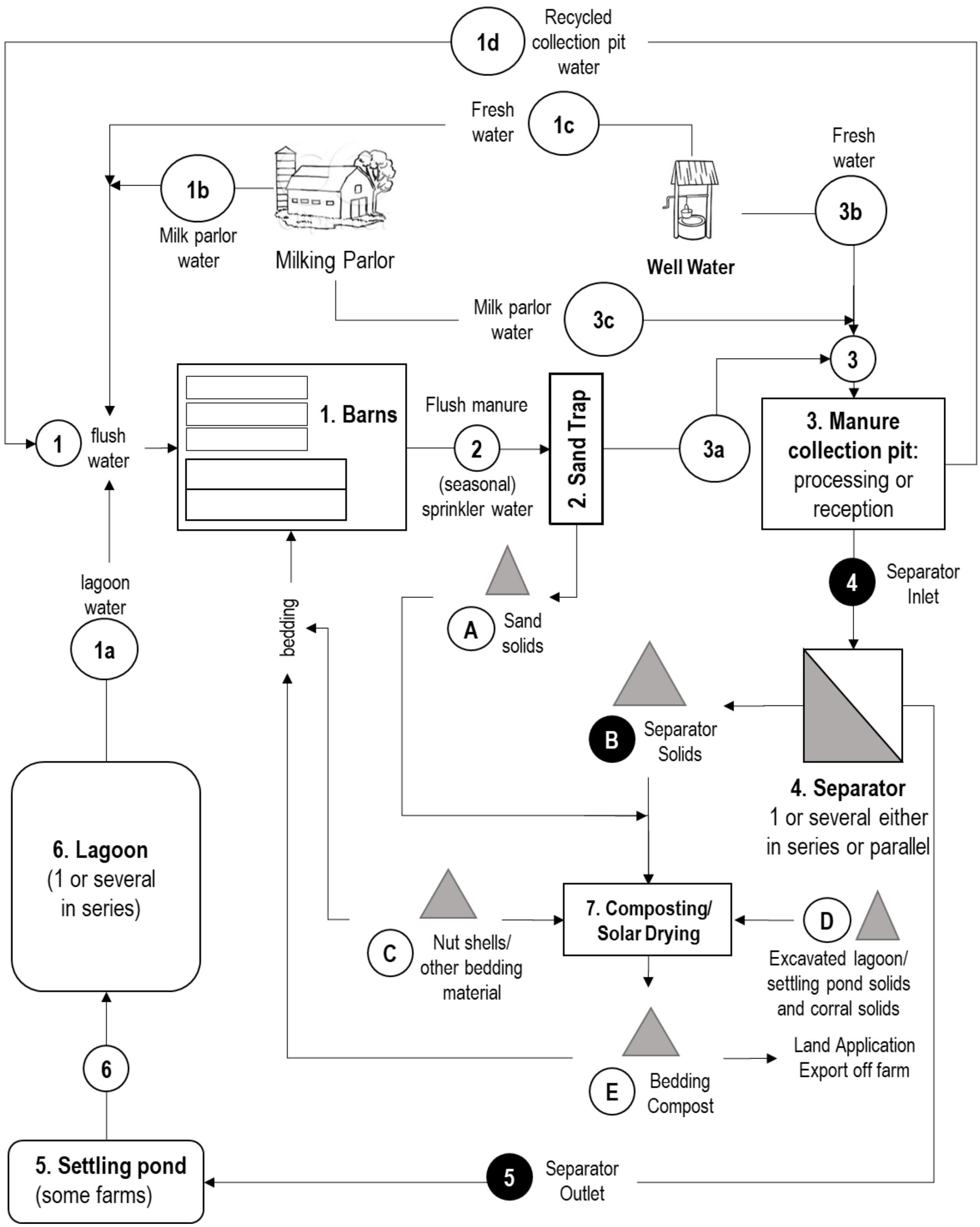

Figure 8. Manure management system process diagram for a typical California dairy (Dark colored flows are sampled flow streams)

Weighing and sampling separator solids
At the end of the sampling period, mechanical separator solids were weighed using front end loaders and/or dump trucks. The hauling trucks were weighted before and after loading using the available scales in most the studied dairies, except the dairy F where the solids were weighted using the scale on a neighbor dairy. Samples of separator solids were collected, in a quart size Ziploc bags, from different locations of solid piles. At least 8 samples were collected from manure piles in each sampling event.

Weeping wall solids were weighed 4-6 weeks after cell filling. Workers excavating the weeping wall transferred solids to a composting ground using large dump trucks. It took roughly 150-200 dump truck loads to empty a cell. During the solid transportation, samples were collected from different locations of the exposed face of the accumulated solids in the weeping wall. Between truck loads, at least three samples were collected, in a quart size Ziploc bags, across the face (bottom, middle, and top) of the solids. The collected solid samples were double bagged and were immediately placed in a cooler and kept on ice until transferred to a refrigerator or freezer back at the BEE lab.

Task 1.2. Sampling solid separators and conducting laboratory experiments and analysis to determine the methane production potential of manure before and after separation

Sampling schedule
Sampling work began in July 2017 and continued through December 2018. Dairies with mechanical solid-liquid separators (Dairies A, B, C, and F) were sampled 4 times each, once per season, for a minimum of 6 and up to 24 hours depending on the dairy and the sampling event. Since the original Dairy D has some issues with solid build up in the pipes, only three sampling trips were conducted for the replacement dairy.

Dairy E, the site of the weeping wall, has 4 cells each taking between 2-4 weeks to fill. Two consecutive cell filling cycles were sampled in September and October 2018. Continuous sampling on the dairy was infeasible. Instead, the project team sampled this site 5 times for a minimum of 24 and up to a 48-hour period per event. Dairy personnel sampled the cells in the interim periods, 3 times a day. Table 6 shows a comprehensive sampling schedule for each dairy. Check marks (✓) indicate completed tasks. More details about each sampling event: description, date, period, and frequency are provided in the results section under the heading for each dairy.

Table 6. Dairy sampling schedule

	2017						**2018**											
Site ID	**7**	**8**	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Dairy A	✓			✓				✓			✓							
Dairy B		✓				✓						✓						
Dairy C		✓			✓				✓			✓						
Dairy D*				✓														
Dairy D									✓			✓			✓			
Dairy E															✓	✓		
Dairy F					✓				✓			✓			✓			

✓: dairy sampling

Completed samplings and analysis

Tables 7, 8, 9, and 10 list the status of sampling work at each dairy as well as the biomethane potential testing, nutrient analysis, and particle size distribution analysis for samples from each dairy. Check marks (✓) indicate completed tasks, “n.s.” indicates nonsampled events; and “n.d.” indicates not determined analysis.

Sampling has been completed in all four seasons on Dairies A, C, and F. Dairies B and D have been sampled during 3 seasons. Biomethane potential testing has been completed for all sampling events..

Table 7. Completed dairy sampling events

Site ID	Technology	Summer	Fall	Winter	Spring
Dairy A	1-stage sloped dual-screen	✓	✓	✓	✓
Dairy B	2-stage sloped dual-screen	✓	n.s.	✓	✓
Dairy C	Advanced multistage	✓	✓	✓	✓
Dairy D	1-stage horizontal scrape-screen	✓	n.s.	✓	✓
Dairy E	Weeping wall	✓	✓	n.s.	n.s.
Dairy F	1-stage sloped single-screen	✓	✓	✓	✓

✓: completed | n.s.: not sampled

Table 8. Biomethane potential testing completed for each dairy

Site ID	Technology	Summer	Fall	Winter	Spring
Dairy A	1-stage sloped dual-screen	✓	✓	✓	✓
Dairy B	2-stage sloped dual-screen	✓	n.s.	✓	✓
Dairy C	Advanced multistage	✓	✓	✓	✓
Dairy D	1-stage horizontal scrape-screen	✓	n.s.	✓	✓
Dairy E	Weeping wall	✓	✓	n.s.	n.s.
Dairy F	1-stage sloped single-screen	✓	✓	✓	✓

✓: completed | n.s.: not sampled

Table 9. Nutrient analysis completed for each dairy

Site ID	Technology	Summer	Fall	Winter	Spring
Dairy A	1-stage sloped dual-screen	✓	✓	✓	✓
Dairy B	2-stage sloped dual-screen	✓	n.s.	✓	✓
Dairy C	Advanced multistage	✓	✓	✓	✓
Dairy D	1-stage horizontal scrape-screen	n.d.	n.s.	✓	✓
Dairy E	Weeping wall	✓	✓	n.s.	n.s.
Dairy F	1-stage sloped single-screen	n.d.	✓	✓	✓

✓: completed | n.d.: not determined | n.s.: not sampled

Particle size distribution has been conducted once on the composite sample in the Spring quarter for each dairy.

Laboratory experiments

The following sections describe laboratory materials and methods as well as methodology for determining separator solids removal efficiencies and methane potential reductions.

Sample processing: compositing and lab analyses

Individual collected samples were measured for TS and VS. They were then mixed together to produce a composite inlet, outlet, and separated solids sample. The volume of each individual sample added to the composite was determined by calculating the weighted contribution of each sample based on separator flow rate, time of separator operation, and total flow during the sampling period. If the flow rate was consistent throughout the sampling event, equal volume of samples were then mixed to make the composite sample. Solids composite samples were created in a similar fashion by mixing equal amounts of solids from individually collected samples.

A diagram of the compositing procedure and laboratory analyses conducted on each composite is illustrated in Figure 9. Composite samples analyzed for pH, TS, VS, biomethane potential, particle size distribution, and nutrient analysis. TS and VS data was used to setup and conduct a biomethane potential test.

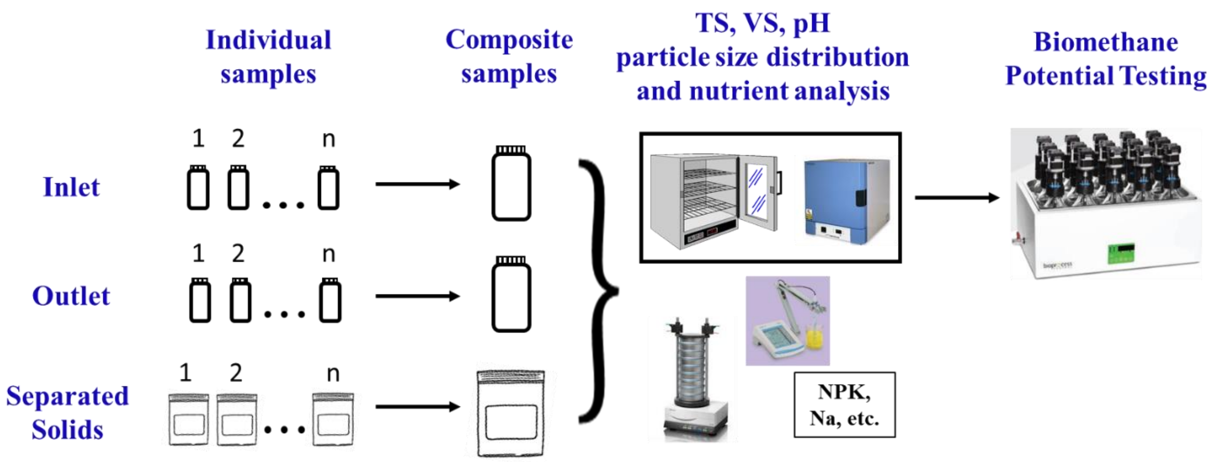

Figure 9. Sample compositing procedure and laboratory analyses
(**Image sources:** Plastic Bag - Shutterstock | Oven - ClipartXtras
Muffled furnace - Cole Palmer™ | BMP Unit - Bioprocess Control™)

Total and volatile solids, pH, and nutrient analyses

Collected samples were returned to the BEE Lab on ice. Individual samples were measured for total (TS) and volatile (VS) solids. TS and VS were measured by drying 25 mL subsamples in an oven (103-105°C) overnight and then combusting in a muffled furnace (550°C) for 3-4 hours (APHA, 1998).

Nutrient analysis and pH on composite samples were performed by Denele Analytical Labs (Woodland and Turlock, CA). Liquid analyses included pH, electrical conductivity, and wet basis measurements of ammoniacal nitrogen, Kjeldahl nitrogen, phosphorus, potassium, sodium, copper, zinc, boron, and magnesium. Solids analyses included moisture content, pH, electrical conductivity, organic matter and dry basis measurements of total nitrogen, phosphorus, potassium, calcium, sodium, copper, iron, boron, zinc, manganese, magnesium, and sulfur.

Particle size distribution analysis

Particle size distribution analysis was conducted, in triplicate, on a composite sample of flush manure from the separator inlet using a Retsch AS200 vibratory sieve shaker in the BEE lab at UC Davis. The test was performed using four U.S. standard test sieves: 1 mm, 500 µm, 250 µm, and 75 µm and in some cases a 3.2 mm or 2 mm test sieve was also used. The 500 and 250 µm sieves were chosen because they were nearly the same size as the minimum screen size of the sloped-screen coarse and fine separator screens (508 and 254 µm). The extra screens were used to prevent excess solid accumulation on any one screen, which results in screen blinding. The final sieve was selected because liquid less than 75 µm is suitable for drip line irrigation.

Solids less than each sieve size pass through by the vibratory action of the sieve shaker. Test sieves were stacked and no more than 500 mL of sample was poured onto the top screen at a time. Liquid was collected in a pan at the base of the sieves. The sieve shaker was operated at 1 amplitude for 1 minute before the top screen was carefully removed. The sieve shaker was operated for 30 seconds intervals and each sieve in the stack was removed one by one for a total sieving time of 2.5-3.5 minutes, depending on the number of test sieves. This process was repeated on 500 mL of composite sample one or two more times for a total replicate volume of 1-1.5 liters. After weighing and recording the net weight of the solids fraction retained on each screen, as well as the liquid on the bottom pan, total and volatile solids the solids and liquid were measured to calculate the total and volatile particle size distribution and the theoretical lab separation efficiency. The same procedure was followed for each sieve in the stack as well as for the final liquid collection pan.

Biomethane potential (BMP) test conditions and parameters

Biomethane potentials of manure samples were measured using the Automatic Methane Potential Test System (AMPTS) from Bioprocess Control AB based in Sweden (Figure 10). The AMPTS consists of: (1) the sample incubation unit where 500 mL bottles containing inoculum and sample are held, (2) the CO_2 fixing unit, which removes carbon dioxide from the biogas, (3) the gas volume measuring device, which measures methane using a tip meter, and (4) the software interface. All samples were measured in duplicate.

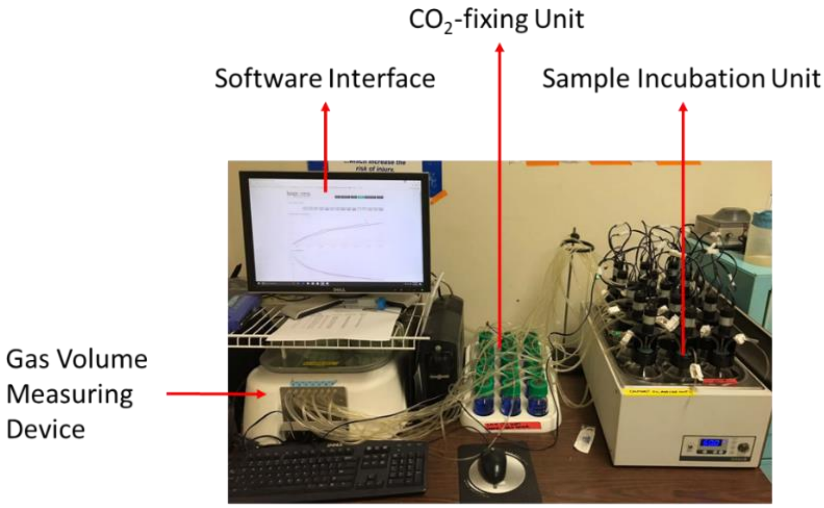

Figure 10. Automatic Methane Potential Test System (AMPTS)

Table 10 summarizes the BMP testing parameters. Composite separator inlet and outlet samples and composite separated solids samples were added to the batch reactors, with total volume of 400 ml, at a loading rate of 5 grams VS per liter and adjusted to a pH of 8.0. All tests were conducted at a food to microorganism ratio of 1. The BMP was run at a thermophilic temperature of 50°C for a digestion time of 21 days, at which point negligible additional methane production was observed.

Table 10. BMP Testing Parameters

Test Parameter	**Value**
Organic loading	5 g [VS]/L
Food to Microorganism (F/M) Ratio	1:1
Temperature	50°C
Initial pH	8.0
Effective volume	400 mL
Test duration	21 days

Task 1.3. Determining efficiencies of different solid separation technologies and developing the correlations between the separation technologies and efficiencies with the methane production potential reduction

The efficiency of different solid separation technologies was determined for the removal selected nutrients N, P, K, Na, and Mg. The efficiency of the separation technology for each of these constituents was determined as follows:

$$\tau_{i=} \frac{M_s \times Cs(i)}{M_{in} \times Cl(i)} \times 100 \qquad \text{Equation 1}$$

Where:
τ_i = efficiency for removal of a component (i)
M_s = mass of the solid separated from each separator, lb, dry basis (db)
Cs (i)= concentration of a component (i) in the solid stream, % db
M_{in} = Mass of the flushed manure entering the separator, lb, wet basis (wb)
Cl (i)= concentration of a component (i) in the inlet manure, % wb

Determination of solids removal efficiency and methane potential reduction

The on-dairy measurements and the laboratory data were used to determine the TS and VS removal efficiencies, and methane potential reduction. The separators' total and volatile solids removal efficiency, and methane potential reduction from the storage lagoon, were determined using Equations 2-4.

TS removal efficiency was calculated by dividing the mass of TS in the separated solids by mass of TS in the inlet (Equation 2a). VS removal efficiency was calculated in the same fashion (Equation 3a). Total solids and volatile solids concentration were interpolated for every time during separator operation by interpolating the individually collected sample TS and VS concentrations. The TS and VS masses of the separated solids were calculated by multiplying the wet mass of separated solids, accumulated during the sampling event, by the TS and VS concentrations of the composite solid samples. The mass of TS and VS in the inlet stream was calculated by multiplying the interpolated TS and VS concentrations by the incremental flow measurements obtained from the flow meter, multiplying by the density of flush manure to convert to mass flows, and integrating the mass flows over the sampling period (Equation 2b and 3b). The density of the flush manure was measured after weighting the mass of a 100 ml of flushed manure that was measured using a volumetric flask. An average density of 0.98 g/mL was used in the calculations. The mass of TS and VS in the outlet stream was calculated by subtracting the mass of TS and VS of the separated solids from the mass of TS and VS determined for the inlet (Equation 2c and 3c).

$$TS_{removal} = \frac{TS_{Solids}}{TS_{In}} \times 100\% \qquad \text{Equation 2a}$$

$TS_{removal}$ = total solids removal efficiency in %;
TS_{Solids} = mass of the weighed total solids in dry tons;
TS_{In} = mass of total solids entering the separator inlet during the flush cycle in dry tons.

$$TS_{In} = \sum_{i-\text{start}}^{i-end} \left(\emptyset_{m\,In} \times TSc_{In}\right)_i \qquad \text{Equation 2b}$$

Start and *end* = flush start and end time, minutes;
$\emptyset_{m\,In}$ = mass flow of flush manure in wet tons by multiplying flush manure density by flow;
TSc_{In} = inlet total solids concentration in %.

$$TS_{Out} = TS_{In} - TS_{Solids} \quad \text{Equation 2c}$$

TS_{Out} = mass of total solids exiting the separator outlet during the flush cycle in dry tons.

$$VS_{removal} = \frac{VS_{Solids}}{VS_{In}} \times 100\% \quad \text{Equation 3a}$$

$VS_{removal}$ = volatile solids removal efficiency in %;
VS_{Solids} = mass of the weighed volatile solids in dry tons;
VS_{In} = mass of volatile solids entering the separator inlet during the flush cycle in dry tons.

$$VS_{In} = \sum_{i\text{-start}}^{i\text{-}end} \left(\emptyset_{m\,In} \times VSc_{In} \right)_i \quad \text{Equation 3b}$$

VSc_{In} = inlet volatile solids concentration in %.

$$VS_{Out} = VS_{In} - VS_{Solids} \quad \text{Equation 3c}$$

VS_{Out} = mass of volatile solids exiting the separator outlet during the flush cycle in dry tons.

Methane reduction potential is defined as the difference in the biomethane potential in the inlet and outlet divided by the biomethane potential in the inlet (Equation 4a). The biomethane potential of the inlet was calculated by multiplying the mass of VS in the inlet by the biomethane potential per unit mass of VS, which was obtained from the BMP test (Equation 4b). The biomethane potential of the outlet was calculated similarly, except that the mass VS in the outlet is calculated by subtracting the mass VS in the inlet by the mass VS in the separated solids (Equation 3c and 4c).

$$CH_{4\,reduction} = \frac{CH_{4\,In} - CH_{4\,Out}}{CH_{4\,In}} * 100\% \quad \text{Equation 4a}$$

$CH_{4\,reduction}$ = reduction in methane potential from separator inlet to outlet in %;
CH_{4In} = biomethane potential of separator inlet volatile solids in ft^3;
CH_{4Out} = biomethane potential of separator outlet volatile solids in ft^3.

$$CH_{4\,In} = VS_{In} * BMP_{In} \quad \text{Equation 4b}$$

BMP_{In} = biomethane potential of separator inlet sample per gram VS in ft^3/ton VS.

$$CH_{4Out} = VS_{Out} * BMP_{Out} \quad \text{Equation 4c}$$

BMP_{Out} = biomethane potential of separator outlet sample per gram VS in ft^3/ton VS.

Objective 2. Analyze the costs and benefits of various solid-liquid separation technologies and develop recommendations for selecting, applying and improving the solid-liquid separation technologies for achieving different levels of methane emission reductions.

Task 2.1. Analyzing and determining the costs and benefits of various solid-liquid separation technologies in relation to methane potential reduction

The efficiencies of various solid liquid separators have been evaluated from a technical stand point in the previous chapters. The following section aims to study the capital and operating and maintenance (O&M) costs of each mechanical separator to provide an economic analysis of the selected separation technologies on California dairies.

An economic model was developed to estimate the costs of the GHG mitigation and the separation of the solids using a project lifetime of 15 years, which is about when the major parts of the mechanical separators and the pumps and mixers in the weeping wall system become worn out and need to be replaced. The capital and O&M costs were collected from the technology vendors and dairy records. The capital costs include the costs of the equipment and the constructions needed to operate them; e.g., the cost of concrete work for the processing pit that is essential not only for providing a homogenous influent in most of the systems but also a buffer capacity during the rainy season as well. The annual O&M costs include the monthly inspection and maintenance provided by the separator manufacturer, as well as the electricity cost.

Calculation of the separator costs

An economic simulation model was developed for each type of the studied mechanical separators. The dairy information, including dairy size and flush schedule, was obtained from the dairy questionnaire shown in Appendix A. The life time of the separators was 15 years, which was determined by separator vendors based on the average service life of the pumps and the mixers. The market interest rate was assumed to be 8%, which was calculated by adding the interest rate of the 15 years risk free US treasury bond (3%) and a 5% risk premium for the investment. Since the separators were installed in different years, the capital costs were converted to the current value by multiplying the inflation rate. The average inflation rate was calculated from equation 5, and assumed to be 1.7% per year.

$$\bar{f} = \left[\frac{C_n}{C_0}\right]^{\frac{1}{N}} - 1 \qquad \text{Equation 5}$$

Where, $\bar{f}$ is the average inflation rate, C_n is the capital cost at the end of year N, C_0 is the capital cost at the base year, which is the year of installation, and N is the number of years.

The capital cost includes the costs of the separators, the pumping system, the processing pit, as well as the concrete work, such as the construction of the separator pad and the stacking slab for the separated manure. Some dairies need to install additional electrical panels to automatically control the separator system, and the electrical service was also included in the initial capital cost.

The capital costs of separators were obtained from the dairy operators or from the vendors of each separators. The annual operating and maintenance (O&M) cost includes the annual maintenance and the electricity costs for operating the separators. The vendor normally provides monthly maintenance for different prices, ranging from $400 to $1000 per month. Monthly maintenance routine includes some visual inspection of the system, greasing and lubricating of the mechanical separator bearings, and checking the pump oil levels. This monthly maintenance is recommended to prevent larger failures of the system.

The costs of the separators were compared based on both the present worth and the annual-equivalent cost methods. The annual O&M cost was converted to the present worth by multiplying the equal-payment series present-worth factor to solve the present value of a series of equal annual payments for a project life of 15 years. The present worth method determines the lump sum amount of cost for each separator system. This analysis allows us to determine the total cost and select the most cost-effective system within the 6 different types of solid liquid separators. On the other hand, the annual-equivalent cost method enables us to select a design alternative not based solely on the lowest initial costs, but also considering all the future costs over the project's useful life. In the annual-equivalent cost analysis, the initial capital costs were converted to annual equivalence by multiplying the capital recovery factor. The equations used to calculate these parameters are as follows:

$$P = A \times ES \quad \text{Equation 6}$$

$$ES = \left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \quad \text{Equation 7}$$

$$A = P \times CR \quad \text{Equation 8}$$

$$CR = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] \quad \text{Equation 9}$$

Where P is the present worth, A is the annual equivalent cost, ES is the equal-payment series present-worth factor, CR is the capital recovery factor, i is the interest rate, and N is the project lifetime.

To compare different dairies at the same scale, the final cost results were normalized by the average number of milking cows on the dairy.

Task 2.2. Developing recommendations for selecting effective solid-liquid separation technologies for methane emission reductions.

The calculated efficiencies of the separation technology and the laboratory analysis data was combined to develop recommendations for the technologies that potentially provide the most effective methane emission reduction in the lagoons.

Results and Discussion

Dairy A: 1-stage sloped dual-screen separator

Dairy A description: dairy operation, manure management, flush cycle, and separator

Dairy A is a 2,000 head milking cow facility with another 1,400 to 1,800 dry cows, calves, and heifers. The dairy has 4 free stall barns, 7 dry cow pens, hospital free stalls, another set of close up free stalls, and a milking parlor. Lactating (milking) cows are housed in freestall barns and are allowed to roam freely between barns and exercise pens, except during cold weather months when they are locked into the freestall barns 24/7. Dry cows, calves, and heifers are housed fulltime in corrals. The owner of Dairy A also owns a dairy just down the road where he houses and raises between 1,100 and 1,300 more replacement cows. Sprinklers are installed in the freestall barns and turn on automatically in periods of warm weather.

The facility has had significant site upgrading done in the past two and a half years, replacing the old reception pit for a new concrete processing pit and adding a new single stage sloped dual-screen separator. The new processing pit includes a sand lane, followed by a reception pit where flush manure is collected and agitated before being pumped over to the separator. The flush manure in the reception pit is also recycled for flushing and provides a majority of the flush water. The balance of the flush water comes from liquid storage in the lagoon, which is periodically recharged with groundwater as needed.

Dairy A employs a flush manure management system. Figure 11 depicts manure management on the dairy. Points 3, 4, and 5 (separator inlet, outlet, and solids) were regularly sampled for detailed analyses and biomethane potential testing. Samples were also taken infrequently from points 1, 2, 6, and 7 (flush manure, sand, bedding, and lagoon flush water) for secondary spot-testing only. Once generated in the barns and corals, manure is flushed into a processing pit (flow 1). The lane around the main pit captures sand (flow 2). Sand is removed about once per week by an excavator. The hexagonal reception pit in the middle descends several feet down and is calculated to have a storage volume of about 7,000 gallons. Flush manure collects in this pit and is agitated before either being pumped back through the barns for use as flush water or over the separator (flow 3). After passing through the separator, flush water enters into the second lagoon (flow 4). The fact that the separator is able to adequately process all of the dairies' flush water has allowed the owner the luxury of taking the first lagoon out of operation for cleaning during the summer of 2017. The dairy also has 2 settling ponds, however, those are not currently being used.

The separator is designed with two sloped screens that receive flush manure at the top. Solids are removed by gravity separation as flush manure flows down the screens. The screen size is non uniform down the length of the screen. The top two-thirds section of the screen has separation of 0.020 inches (508 µm) and the bottom one-third is 0.025 inch (635 µm). Solids collected at the bottom are pressed through an auger screw press and transported by a perforated conveyor belt before being dropped onto a concrete pad where they form a pile (flow 5). The solids are windrowed and solar dried before either being recycled as bedding or land applied (flow 6). Screened liquids flow into a series of two lagoons (flow 4).

Dairy A flushes its barns 3 times per day at 4 AM, 12 PM, and 8 PM. The flush cycles last just under 4.75 hours. The barns are flushed by a series of 29 flush valves, 6 of which are supplied with "cleaner" water directly from the lagoon, while the remaining 23 get recycled flush water from the reception pit. Recycled flush water from the reception pit is pumped by the flush pump, shown in the Figure 12A.

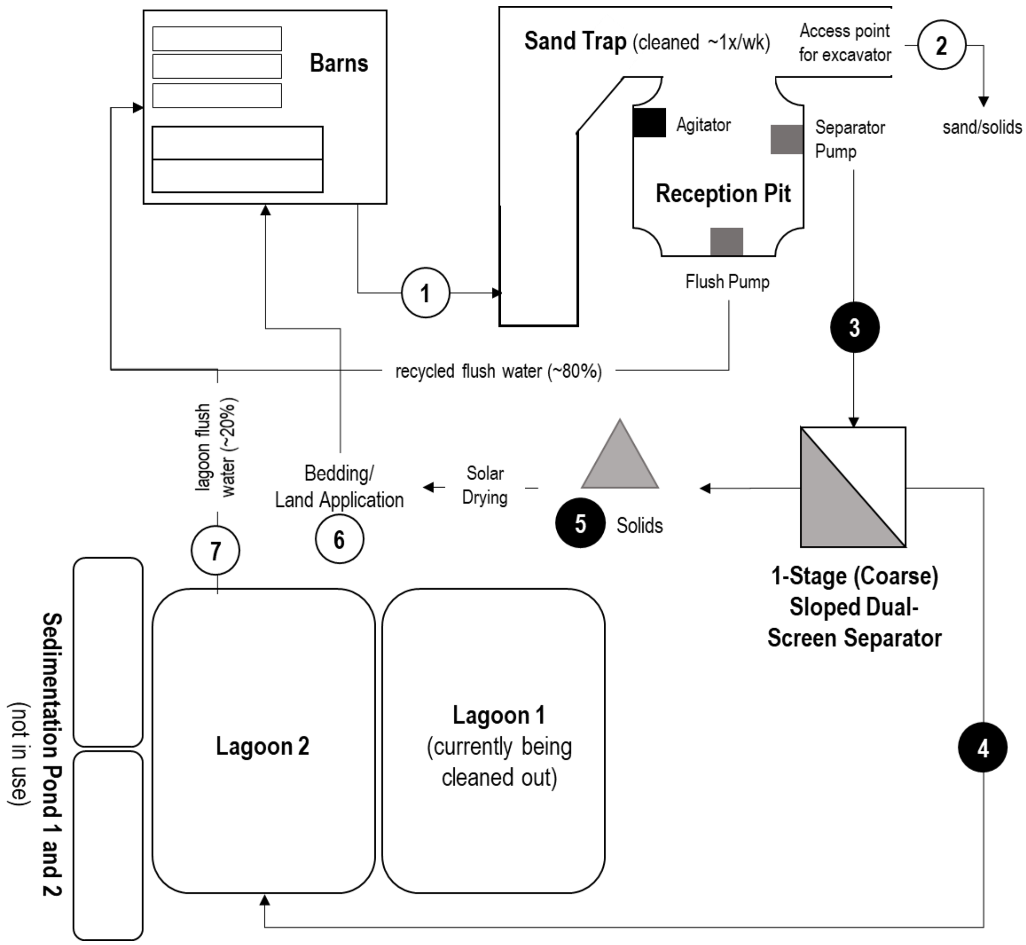

Figure 11. Dairy A: Manure management system process diagram
(**3:** separator inlet; **4:** separator outlet; and **5:** separator solids were sampled streams)

Figure 12. Dairy A: **(A)** flush pump in the reception pit, and
(B) separator outflow into the first storage lagoon

Flushing takes place in non-concurrent cycles of about 7 minutes per valve with two significant delay periods of 40 and 35 minutes during which no flushing occurs (Table 11 and Figure 13). These delay periods occur after the 11th and then the 19th flush valve. Flush water from the dry pens occurs early on in the flush cycle, which is probably why 4 of the 6 lagoon flushes, with “cleaner” water, occur in the first half of the cycle. The last flush is also a lagoon flush completing the 4.75 hour cycle. Figure 13 is a map of the dairy and flush valves and Table 11 is the flush sequence at Dairy A.

The flush valves and flush pump are controlled by a timer. The separator pump located in the processing pit (Figure 13A), which sends flush water to the separator, is controlled by two level sensors. The pump turns on when the water level reaches the upper level sensor and stops when flush water has been drawn down enough to trigger the lower level sensor. The level sensors are built with an override, which prevents the separator pump from activating as long as the flush pump is on. Despite this override, flush water does not overwhelm the reception pit. The delay periods of 40 and 35 minutes have been built into the flush scheduled at about a third and two-thirds of the way through the flush cycle. The flush pump turns off during these two delay periods, allowing the separator pump and separator to turn on and draw down the reception pit. Thus, the separator can turn on twice during each flush cycle and immediately following the end of the last flush. The separator also can turn on at any point between flush cycles if the water level in the reception pit triggers the upper level sensor.

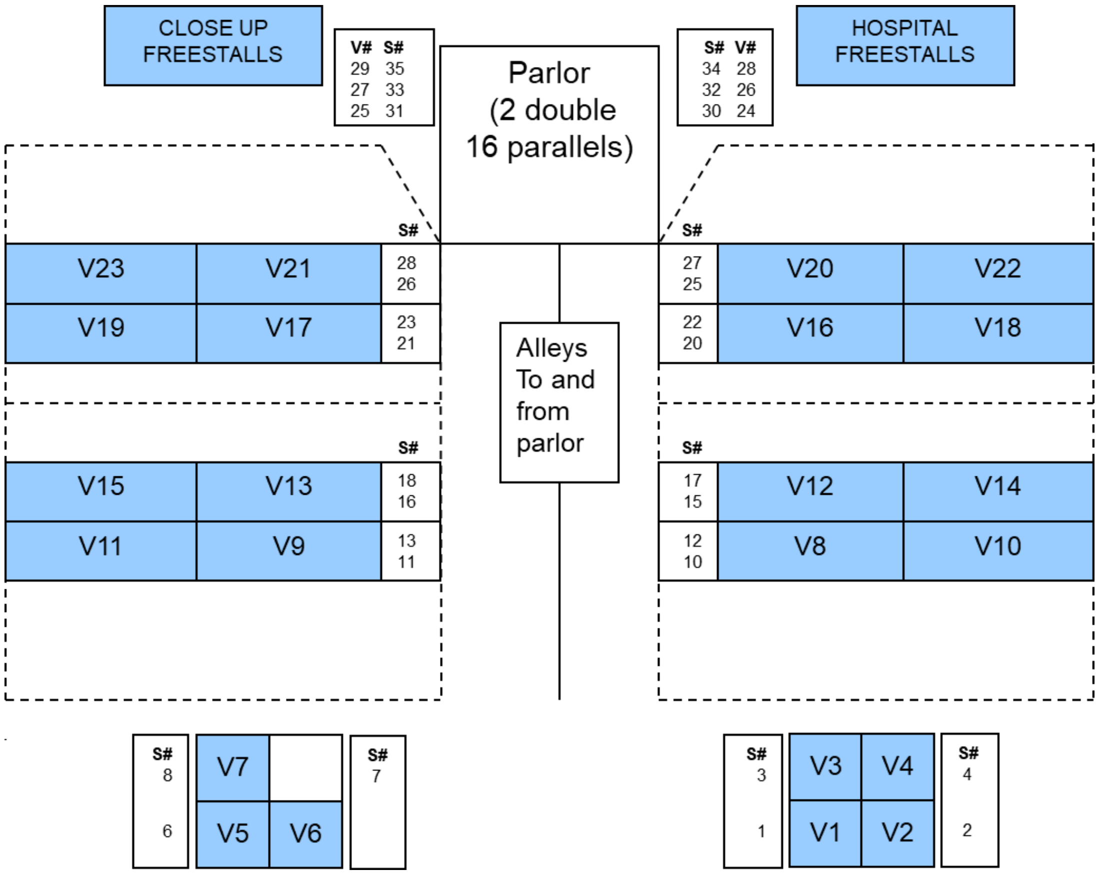

Figure 13. Dairy A: Flush valve map

Table 11. Dairy A: Flush sequence

Seq. (#)	Valve (#)	Duration (mins)	Seq. (#)	Valve (#)	Duration (mins)	Seq. (#)	Valve (#)	Duration (mins)	Seq. (#)	Valve (#)	Duration (mins)	Seq. (#)	Valve (#)	Duration (mins)
1	1	7 mins	9	NA	**Delay** 0 mins	17	14	7 mins	25	20	10 mins	33	27	7 mins
2	2	7 mins	10	8	7 mins	18	15	7 mins	26	21	7 mins	34	28	7 mins
3	3	7 mins	11	9	7 mins	19	NA	**Delay** 0 mins	27	22	7 mins	35	29	7 mins
4	4	7 mins	12	10	7 mins	20	16	7 mins	28	23	7 mins			
5	NA	**Delay** 0 mins	13	11	7 mins	21	17	7 mins	29	NA	**Delay** 0 mins			
6	5	7 mins	14	NA	**Delay** 40 mins	22	18	7 mins	30	24	7 mins			
7	6	7 mins	15	12	10 mins	23	19	7 mins	31	25	7 mins			
8	7	7 mins	16	13	7 mins	24	NA	**Delay** 35 mins	32	26	7 mins			

Potential separator operation-Lagoon flush / Potential separator operation / Processing pit water

Figure 14. Dairy A: **(A)** separator**, (B)** inlet pipe and flow meter**, (C)** inlet/outlet sampling points, and **(D)** solids pile under the separator

Sampling event description: dates, sampling period and frequency

Table 12 lists the date of each sampling event, the sampling period, and sample collection frequency on Dairy A. The separator on Dairy A was evaluated in July 2017, October 2017, February 2018, and May 2018. Separator performance was evaluated over a 24-hour period, from noon to noon. Samples were collected at a frequency of 10 to 30 minutes depending on the sampling event.

Table 13 shows an inventory of the dairies' herd at the time of sampling. The table breaks down the herd by calves 0-3 months, 4-15 months, heifers older than 15 months, milking cows, and dry cows. Milking cows were free to roam between freestall barns and corrals during the summer, fall, and spring sampling events; however, they were locked into the freestall barns during winter due to the cold weather and muddy conditions in the corrals.

Table 12. Dairy A: Sampling dates, periods, and frequency

Season	Date	Sampling period	Sampling frequency
Summer	July 11-12th, 2017	24 hours	10-30 mins
Fall	Oct 30-31st, 2017	24 hours	10-15 mins
Winter	Feb 20-21st, 2018	24 hours	10-15 mins
Spring	May 30-31st, 2018	24 hours	15 mins

Table 13. Dairy A: Herd size in different seasons

Age	Summer July 2017	Fall Oct 2017	Winter Feb 2018	Spring May 2018
0-3 Month	414	0	NA[1]	NA[1]
4-15 Month	369	831	NA[1]	NA[1]
Heifers>15 Mo	695	277	NA[1]	NA[1]
Milking	2,080	2,055	2,082	NA[1]
Dry	258	282	322	NA[1]
Total	3,816	3,445	NA[1]	NA[1]

1: Data not available

Dairy A results: Inflow data, TS/VS, pH, methane potential, particle size distributions and nutrient analysis

Separator operation and inflow data

Figures 15, 16, 17, and 18 show the inflow of flush manure to the separator during the 24-hour sampling period in different seasons. Inflow rate is indicated the left axis and shown in grey while total inflow passing through the separator is indicated on the right axis and shown in black.

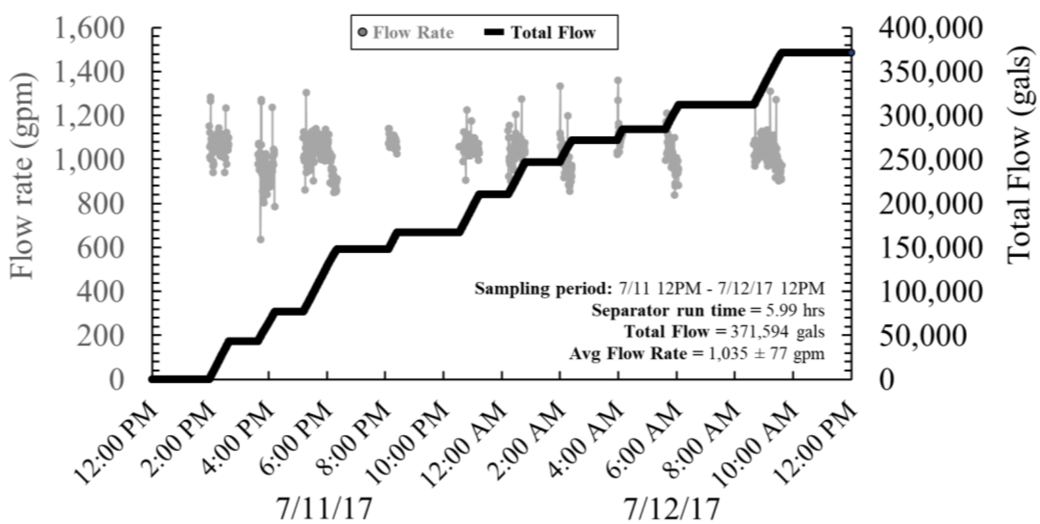

Figure 15. Dairy A: Manure inflow rate and cumulative manure for the summer

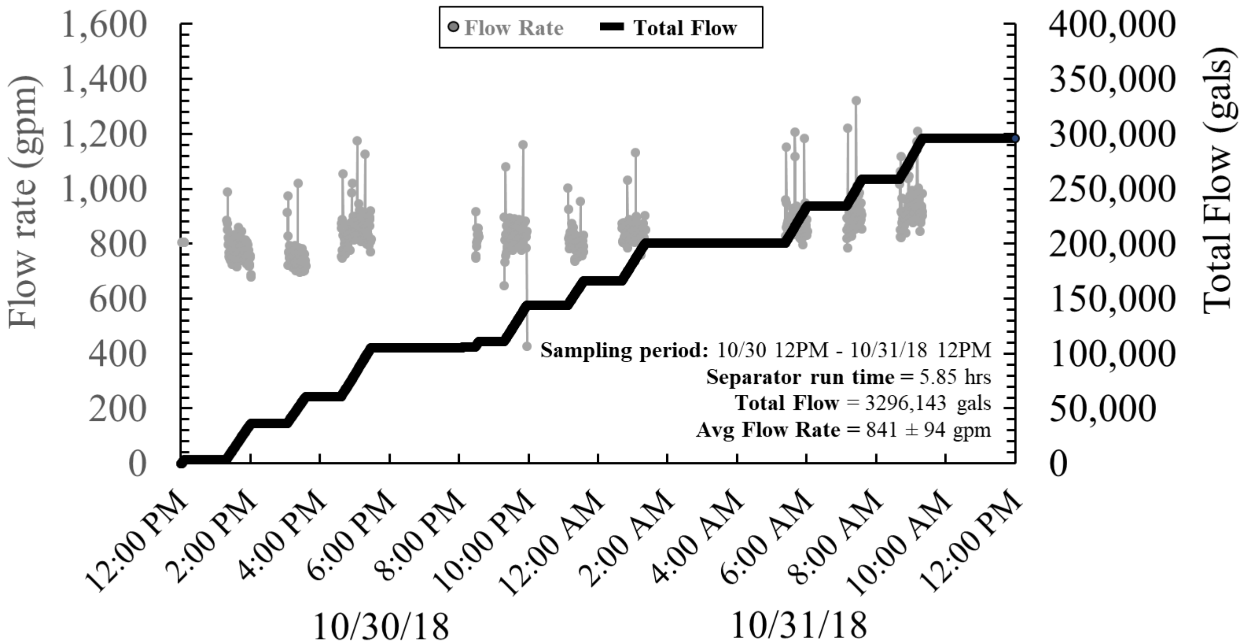

Figure 16. Dairy A: Manure inflow rate and cumulative manure for the fall

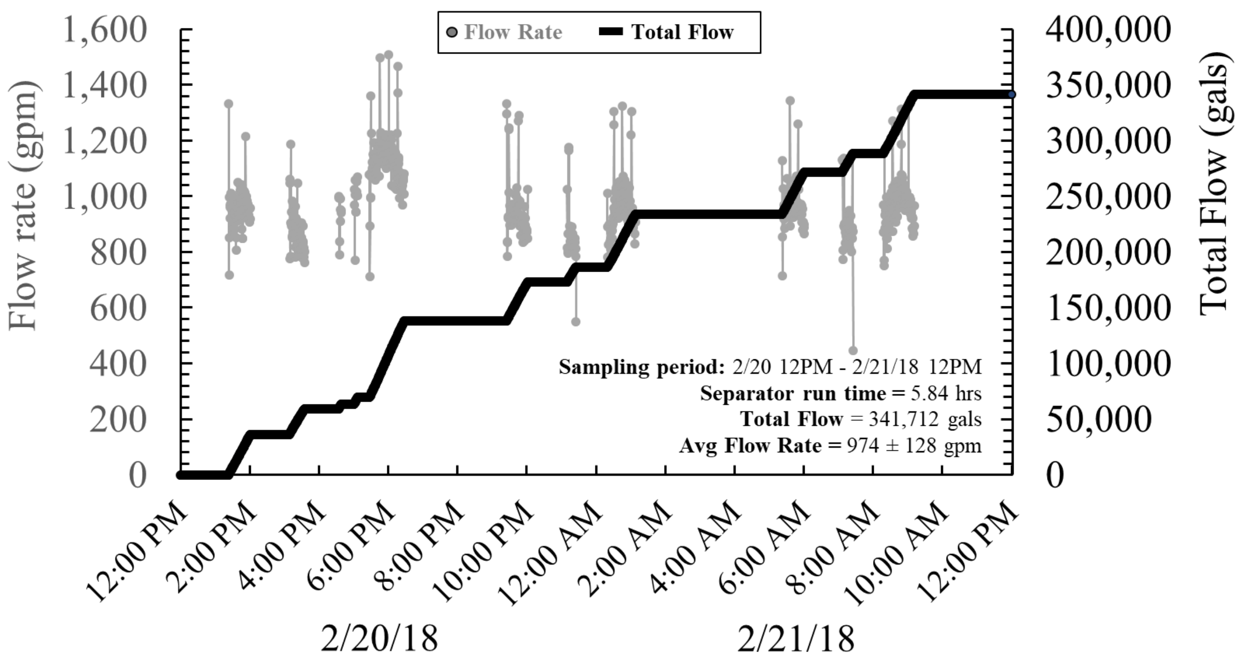

Figure 17. Dairy A: Manure inflow rate and cumulative manure for the winter

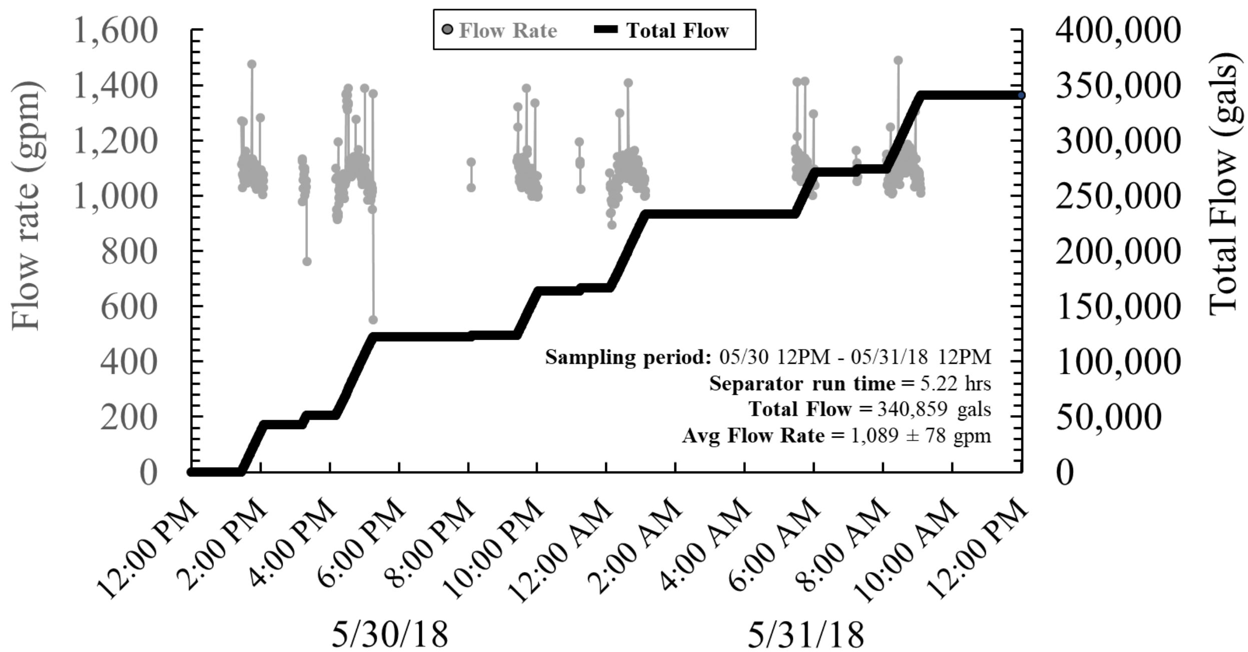

Figure 18. Dairy A: Manure inflow rate and cumulative manure for the spring

Table 14 summarizes the separator operation during each sampling event at Dairy A. The separator was evaluated over 24 hours during each event. The separator ran for nearly 6 hours, about the same length of time during the summer, fall, and winter samplings; however, it was only on for 5.22 hours during the spring sampling event. The separator processed over 340,000 gallons or more of flush manure during the summer, winter, and spring events, but processed just under 300,000 gallons during the fall event. The flow rate of flush manure processed over the dual-screen separator was also less in the fall than the other seasons.

Table 14. Dairy A: Separator flow data in different seasons

Parameter	**Units**	**Summer** July 2017	**Fall** Oct 2017	**Winter** Feb 2018	**Spring** May 2018	**Average** 4 seasons
Sampling period	hrs	24	24	24	24	24
Operating time	hrs	5.99	5.85	5.84	5.22	5.73 ± 0.34
Total inflow	gals	371,594	296,143	341,712	340,859	337,577 ± 31,101
Inflow rate, average	gpm	1,035 ± 77	841 ± 94	974 ± 128	1,089 ± 78	985 ± 107
Separated solids	lbs, wb	141,420	100,620	112,020	121,180	118,810 ± 17,261

Total and Volatile Solids, and pH

Table 15 shows total solids and volatile solids concentrations and pH of separator inlet, outlet, and solids in different seasons. The inlet pH is consistently the lowest followed by the outlet and solids pH.

Table 15. Dairy A: Total and volatile solids concentration (%, wet basis), and pH of separator inlet, outlet, and solids in different seasons

Sample	**Parameter**	**Summer** July 2017	**Fall** Oct 2017	**Winter** Feb 2018	**Spring** May 2018
Inlet	TS	1.98 ±0.64*	1.57 ± 0.22	2.59 ± 0.23	2.03 ± 0.44
	VS	1.34 ± 0.64	1.12 ± 0.18	1.85 ± 0.20	1.49 ± 0.37
	pH	6.9	7.4	7.4	7.1
Outlet	TS	1.53 ± 0.45	1.14 ± 0.14	1.98 ± 0.11	1.27 ± 0.17
	VS	0.94 ± 0.24	0.71 ± 0.09	1.26 ± 0.09	0.80 ± 0.12
	pH	7.3	7.5	7.6	7.3
Solids	TS	19.64 ± 0.35	18.95 ± 0.22	18.32 ± 0.62	20.62 ± 0.22
	VS	17.32 ± 0.55	17.36 ± 0.25	16.70 ± 0.62	18.29 ± 0.19
	pH	7.4	7.9	8.3	7.7

*Standard deviation

Biomethane potential testing

Table 16 shows BMP of composite samples for each sampling event. Biomethane potential of the separator inlet and outlet are generally about the same, as seen in the summer, fall, and winter seasons. However, BMP data from the spring season deviates from this trend with biomethane potential of the inlet lower than the outlet. Generally, separator solids have a lower biomethane potential than either of the liquid streams; however, data from the summer sampling deviates from this trend, with separated solids biomethane potential was higher than that of the inlet and outlet potentials. Figure 19 shows biomethane potential of Dairy A separator inlet, outlet, and solids biomethane potential test data from the different seasons.

Table 16. Dairy A: Biomethane potential (mL/g[VS]) of separator inlet, outlet, and solids in different seasons

Sample	**Summer** July 2017	**Fall** Oct 2017	**Winter** Feb 2018	**Spring** May 2018
Inlet	151.8 ± 3.2[1]	199.8 ± 15.1	265.1± 6.5	202.0 ± 1.7
Outlet	156.2 ± 9.2	207.3 ± 6.2	253.8 ± 16.0	237.8 ± 9.3
Separated solids	178.5 ± 9.4	107.8 ± 3.3	160.5 ± 12.7	113.0 ± 0.0

1: Average values ± standard deviation between two duplicate reactors

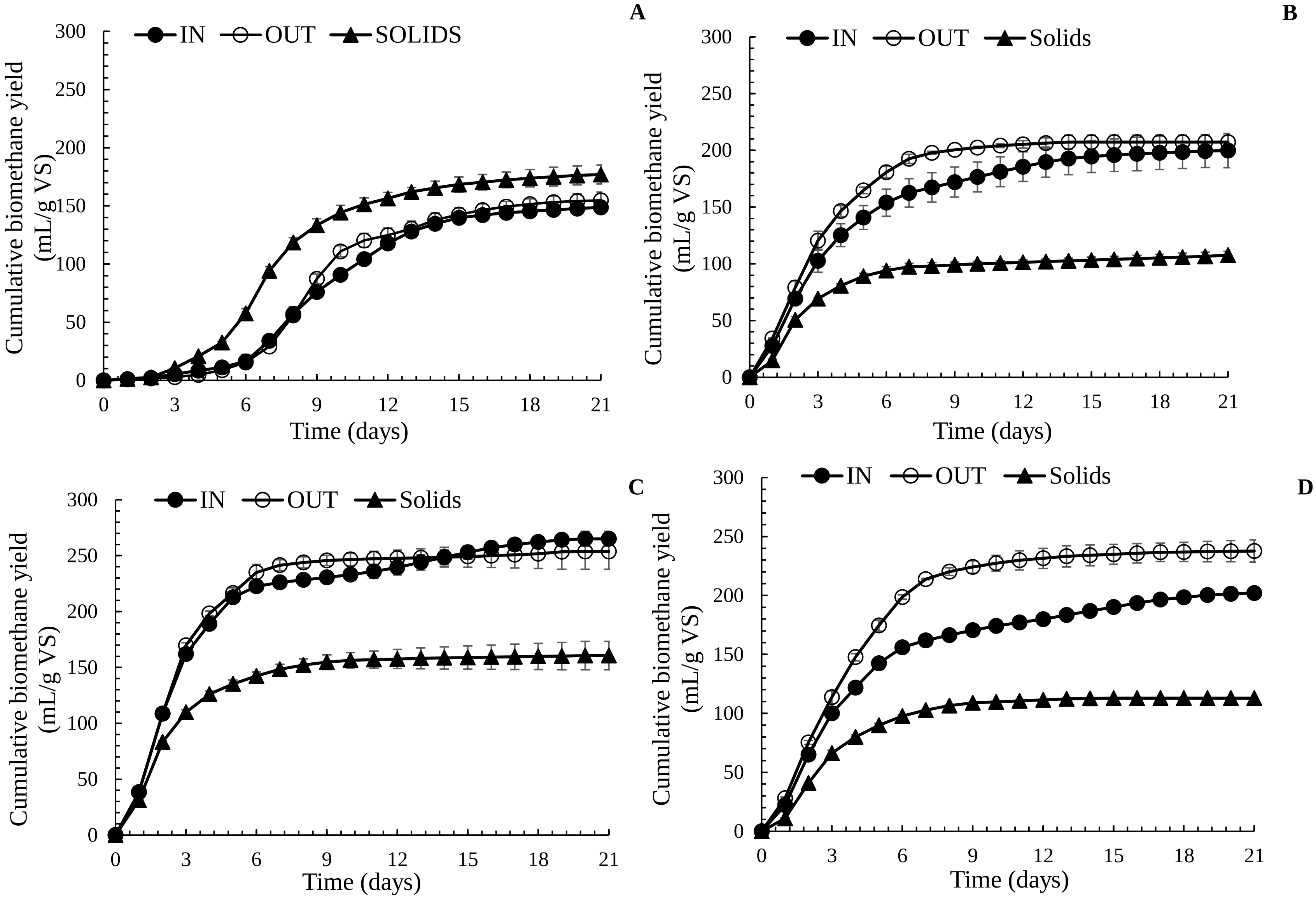

Figure 19. Dairy A: Cumulative biomethane yield in different seasons. **A:** Summer; **B:** Fall; **C:** Winter; **D:** Spring. Y error bars are standard deviations

Particle size distribution analysis

Figure 20 shows the particle size distribution of the composite flushed manure collected from Dairy A during the Spring quarter. Over 31% of the TS contained particles ≥ 1 mm. The particles sizes of < 1mm and ≥ 500µm; < 500 µm and ≥250µm; and < 250 µm and ≥ 75µm represented 9.5%, 8.3%, and 8.6%, respectively. The particle sizes that passed the sieves and went in the liquid stream (< 75 µm) represented 41.8% of TS. The VS contents were relatively higher than the TS contents of particle sizes > 250 µm; especially for the particle sizes of > 500µm, meaning the coarse solid fraction had a higher organic content.

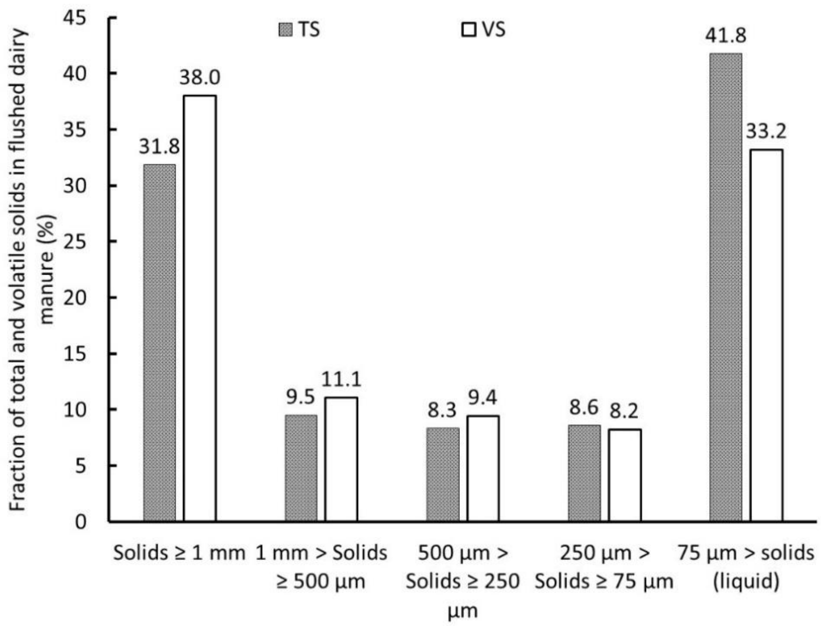

Figure 20. Particle size distribution of the flushed manure on Dairy A

Nutrient analysis

The nutrients concentration in liquid and solid streams are shown in the appendices Tables B1 and B2. The removal efficiency of selected nutrients for all the studied seasons are shown in Table 17. As can be seen the average removal efficiency of N, P, K, Na, and Mg were 18.79%, 34.73%, 6.60%, 5.68%, and 35.82%, respectively. The highest removal efficiencies for the selected nutrients were determined during the summer season. The lowest efficiencies for the removal of Na, and K might be attributed to the fact that they soluble in the liquid and could not be separated over the separator screens.

Table 17. Removal efficiencies (%, of the separator inlet) of selected nutrients for Dairy A.

Element	**Summer**	**Fall**	**Winter**	**Spring**	**Average**
Nitrogen	30.09	19.87	16.08	9.11	18.8
Phosphorus	61.71	36.60	28.53	12.09	34.7
Potassium	9.13	6.00	5.51	5.74	6.6
Sodium	7.91	5.20	4.95	4.66	5.7
Magnesium	47.93	27.91	45.65	21.80	35.8

Dairy A separator solids removal efficiency and methane potential reduction

Table 18 shows separator performance data for each sampling event. The average removal of TS and VS for the four seasons were 41.08% and 52.10%, respectively. The average CH_4 potential reduction was 49.98%. The highest removal efficiencies were achieved in the fall season. TS and VS removal efficiency for the fall season was on average 48.9% and 61.2%, respectively, which was pronouncedly different from the 27.7% and 35.5% TS and VS removal efficiencies in the winter. The regression analysis showed a weak correlation ($R^2 = 0.041$) between the separator efficiency and inflow rate. While there was a strong negative correlation ($R^2 = 0.937$) between the separator efficiency and inlet TS: a lower separator efficiency was obtained with increasing the inlet TS. With the collected data in this study it is not possible to conduct multiple regression analysis to correlate the separator efficiency and both the inflow rate and inlet TS. Methane potential reduction is generally about the same as VS removal efficiency as seen for the summer, fall, and winter samplings. This is because the biomethane potential of the separator inlet and outlet are about the same, as seen in the BMP data. However, the spring sampling event deviates from this trend. The methane potential reduction estimated in the summer, fall, and winter was lower than VS removal efficiency. This may be due to the fact that biomethane potential of the inlet was lower than the outlet, resulting in a lower methane potential reduction for spring.

Table 18. Dairy A: Separator total and volatile solids removal efficiencies (%) and methane potential reduction (%) in different seasons

Parameter	**Summer** July 2017	**Fall** Oct 2017	**Winter** Feb 2018	**Spring** May 2018	**Average**
TS removal efficiency	44.8	48.9	27.7	42.9	41.1
VS removal efficiency	58.4	62.6	35.5	51.9	52.1
CH_4 potential reduction	57.2	61.2	38.2	43.3	50.0

Dairy B: 2-stage sloped dual-screen separator

Dairy B description: dairy operation, manure management, flush cycle, and separator

Dairy B is a 3,000 head milking cow facility. The dairy has 1,000 acres of land with 800 acres accessible to irrigation by the lagoon. This dairy has six free stall barns along with corrals for dry cows. This dairy has a two-stage separator system, with two sloped dual-screen separators in series (Figure 22). The manufacturer of the system is the same as that of Dairy A and the first separator is identical to the mechanical separator on Dairy A. The first separator will be referred to as the coarse or primary separator (Figures 22C, 22D, and 24A) while the second one will be referred to as the fine or secondary separator (Figure 22D).

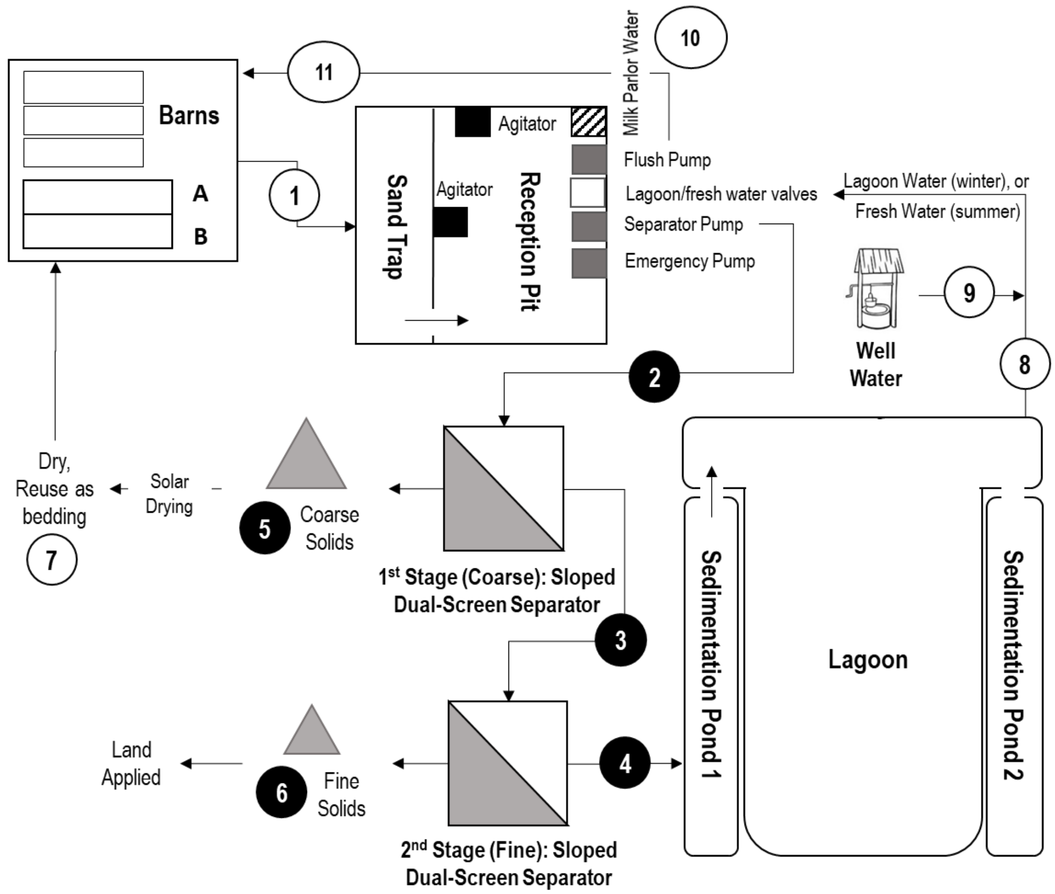

Figure 21. Dairy B: manure management system process diagram
(**2:** system inlet; **3:** system midpoint; **4:** system outlet;
5: coarse solids; and **6:** fine solids were sampled streams)

Dairy B employs a flush manure management system. Figure 21 is a process flow diagram of the dairy with process flows numbered for identification. Sampling points 2, 3, 4, 5, and 6 (system inlet, midpoint, outlet, coarse solids, and fine solids) indicate primary samples points where detailed analyses and BMPs were tested while other points represent secondary sampling points of interest for spot-testing only. Flush manure from the barns (Figure 21, flow 1 and Figure 23A) travels to a sand trap before entering the reception pit. Two agitators in the pit mix up the flush manure and send it either back into the barns for continued flushing or over to the coarse separator (Figure 21, flow 2). The first separator takes out coarse solids (flow 5). These solids are windrowed and solar dried (Figure 24C). They are reapplied to the barns either on their own or after amendment with almond shells as bedding. The screened flush manure moves onto the fine separator (Figure 21, flow 3). This separator removes fine solids, which are land applied for fertilizer (flow 6). Screened flush manure from the fine separator moves onto a sedimentation pond (flow 4 and Figure 24B) and from there into the liquid storage lagoon.

The separators are designed with two vertically sloped screens that receive flush manure, in parallel, at the top of the screen. Solids are removed by gravity separation as flush manure flows down the screens. Solids collected at the bottom are pressed through an auger screw press and transported down a porous conveyor belt, designed to remove more liquid, before being dropped onto a concrete pad where they form a pile (Figure 21, flow 5 and flow 6). The coarse solids are moved to windrowed piles where they are solar dried for several weeks before being recycled as bedding. Sometimes the coarse solids are amended with almond shells before being used as bedding. The fine solids are land applied as fertilizer (Figure 24). Screened liquids flow into a sedimentation pond and then into the liquid storage lagoon (Figure 21, flow 4).

Figure 22. Dairy B: **(A)** flow meter installed on coarse separator inlet, **(B)** two mechanical separators, **(C)** coarse separator, and **(D)** flush manure flowing over separator screen

The separator screens possess a varied grating size down the length of the screen. The coarse separator possesses 0.020 inches (508 µm) screen size over the top two-thirds of the screen and a 0.025 inch (635 µm) over the bottom one-third. The fine separator possesses 0.010 inches (254 µm) screen size over the top two-thirds of the screen and a 0.015 inch (381 µm) over the bottom one-third. Solids from the fine separator are wetter than the coarse separator, which is why the fine separator also has a belt press built into the send of the separator for extra solids dewatering.

Flush water is a combination of fresh water, milk parlor water, and lagoon water. In warm weather months, when fields are being irrigated, fresh water is exclusively used for flushing. Flushing with fresh water makes for cleaner lanes, according to the dairy operator, and the extra water is used out of the lagoon for crop irrigation. In the cooler months, lagoon water or a combination of lagoon and fresh water is used to flush the lanes. During these months, the dairy operator no longer irrigates from the lagoon, and due to limited liquid storage, recycles lagoon water for flushing lanes.

Figure 23. Dairy B: **(A)** flush manure from sand trap into reception pit, **(B)** reception pit, **(C)** separator pump, and **(D)** flush manure and milk parlor process water into reception pit

Dairy B flushes its barns and corrals 3 times a day. Rather than flushing the entire dairy during each flush, the dairy operator has split all the dairy barns into two blocks and performs a flush on each block independently. The 6 flush cycles start at 10 AM, 2 PM, 6 PM, 10 PM, 4 AM, and 6 AM. The initial flush is done with fresh water and is continuously recycled out of the reception pit over the course of the next 4 hours of flushing. Unlike Dairy A, where the separator turns on and off 3 times per flush, on Dairy B mechanical separation takes place in one continuous interval, with the separators operating for the final 1.3-1.5 hours of the cycle.

Figure 24. Dairy B: **(A)** coarse separator, **(B)** screened flush manure into sedimentation pond, and **(C)** windrow piles

Dairy B sampling event description: dates, sampling period and frequency, and weather

Table 19 lists the sampling dates in the summer, winter, and spring seasons at Dairy B.

Table 19. Dairy B: Sampling dates, periods, and frequency

Season	Date	Sampling period	Sampling frequency
Summer	August 2nd, 2017	24 hours	10-15 mins
Winter	Dec 28th, 2017	8 hours	15 mins
Spring	June 20th, 2018	8 hours	15 mins

Dairy B results: Inflow data, TS/VS, pH, methane potential, particle size distribution and nutrient analysis

Separator operation and flow data

Figures 25, 26, and 27 show the inflow of flush manure to the separator in different seasons. Inflow rate is indicated on the left axis and shown in grey while total inflow passing through the separator is indicated on the right axis and shown in black.

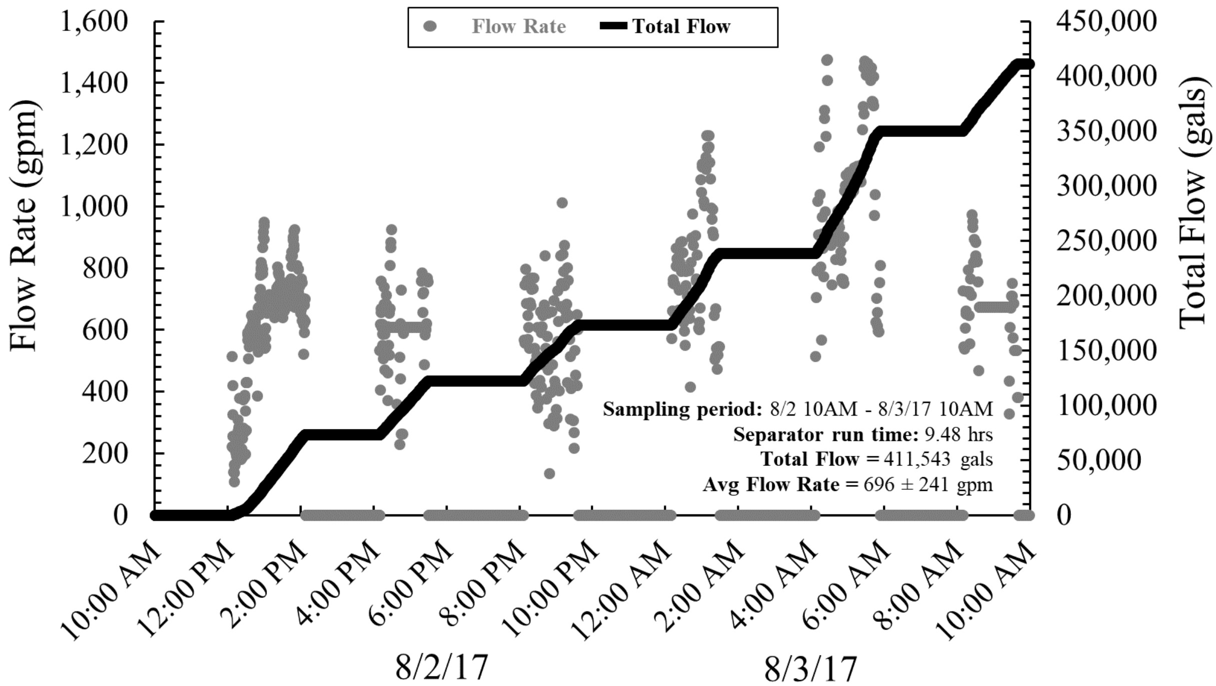

Figure 25. Dairy B: Manure inflow rate and cumulative manure for the summer

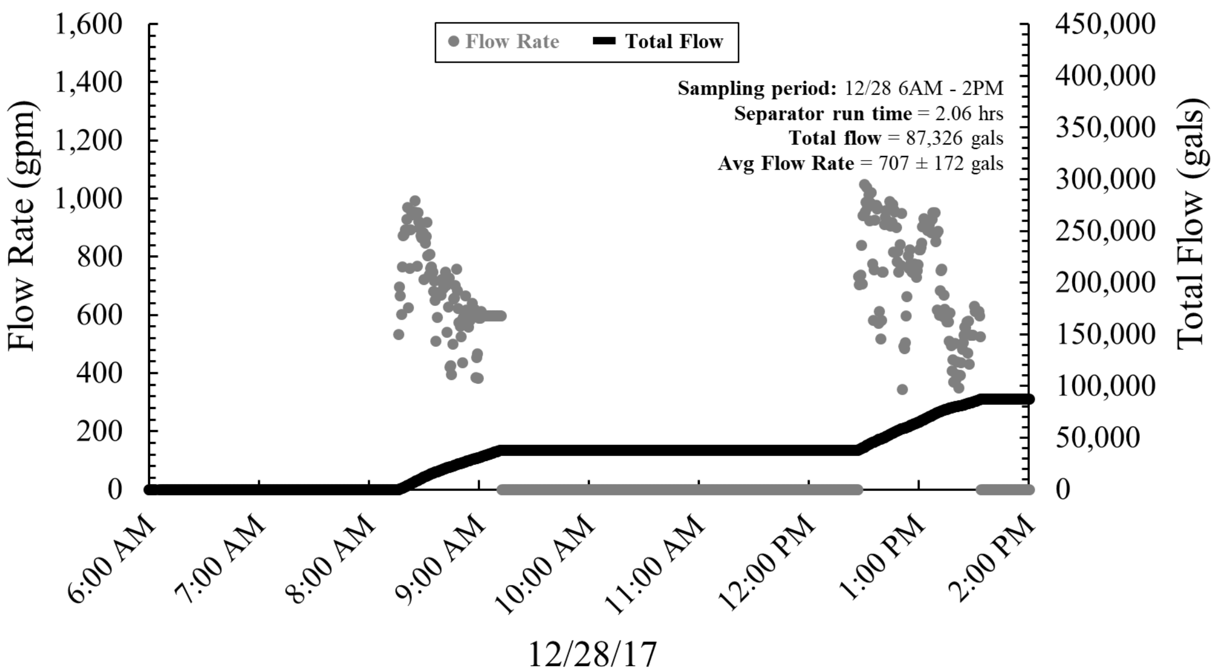

Figure 26. Dairy B: Manure inflow rate and cumulative manure for the winter

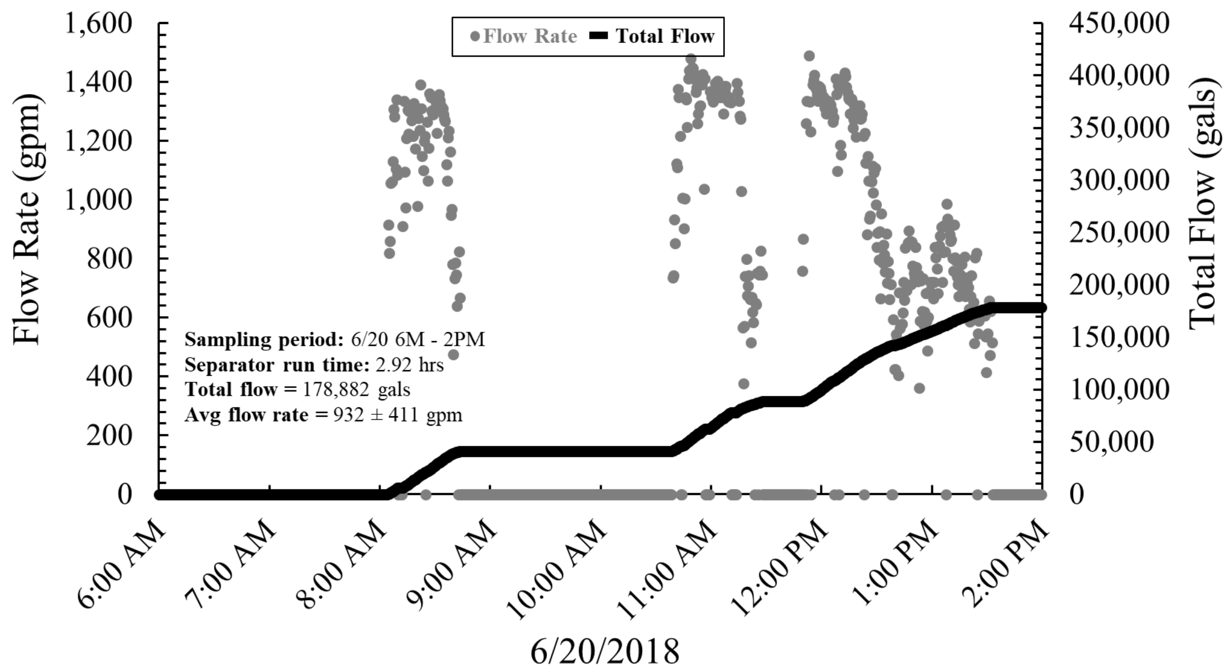

Figure 27. Dairy B: Manure inflow rate and cumulative manure for the spring

Table 20 summarizes the separator operation during each sampling event at Dairy B. The separator was evaluated over 24 hours during the summer and 8 hours in the winter and spring. For comparison, the separator operated for 3.16 hours per 8-hour period in the summer sampling event compared to 2.06 and 2.92 hours in the winter and spring events. The separator processed 137,191 gallons on average per 8 hours in the summer, compared to 87,326 and 178,882 gallons in the spring. The inflow rate in the spring season was higher (932 ± 411 gpm) than that in the summer (696 ± 241 gpm), and winter (707 ± 172 gpm).

Table 20. Dairy B: Separator flow data in different seasons

Parameter	**Units**	**Summer** August 2017	**Fall**	**Winter** Dec 2018	**Spring** June 2018
Sampling period	hrs	24	NA[1]	8	8
Operating time	hrs	9.48	NA	2.06	2.92
Total inflow	gals	411,543	NA	87,326	178,882
Iflow rate, average	gpm	696 ± 241	NA	707 ± 172	932 ± 411
Solids 1	lbs, wb	193,736	NA	77,480	73,920
Solids 2	lbs, wb	29,540	NA	563	8,280

1: No fall testing

Total and Volatile Solids, and pH

Table 21 shows total solids and volatile solids concentration and pH of separator inlet, outlet, and solids in different seasons, respectively. The pH data was for composite samples from separator inlet, outlet, and solids for each sampling event. The inlet pH was consistently the lowest followed by the midpoint, outlet, coarse separator solids, and fine separator solids.

Table 21. Dairy B: Total and volatile solids concentration (%) and pH of separator system inlet, midpoint, outlet, and solids 1 and 2 in different seasons

Sample	Parameter	**Summer** Aug 2017	**Fall**	**Winter** Dec 2018	**Spring** June 2018
Inlet	TS	2.53 ± 0.77[1]	NA[2]	3.73 ± 0.30	3.50 ± 0.39
	VS	1.96 ± 0.67	NA	2.76 ± 0.23	2.55 ± 0.26
	pH	6.7	NA	7.4	6.8
Midpoint	TS	1.75 ± 0.29	NA	2.99 ± 0.08	2.52 ± 0.35
	VS	1.21 ± 0.18	NA	1.94 ± 0.04	1.51 ± 0.12
	pH	6.9	NA	7.7	7.1
Outlet	TS	1.55 ± 0.25	NA	2.85 ± 0.19	2.21 ± 0.17
	VS	1.05 ± 0.17	NA	1.87 ± 0.11	1.45 ± 0.12
	pH	6.9	NA	7.4	7.7
Solids 1	TS	24.22 ± 1.70	NA	20.96 ± 1.10	23.98 ± 0.30
	VS	20.98 ± 1.65	NA	18.88 ± 1.13	19.76 ± 0.32
	pH	7.0	NA	8.4	7.9
Solids 2	TS	25.59 ± 0.87	NA	22.81 ± 0.16	26.03 ± 0.13
	VS	18.53 ± 0.29	NA	17.02 ± 0.09	16.23 ± 0.12
	pH	7.5	NA	8.5	8.2

1: TS% and VS% are based on 4 out of the 6 flush cycles sampled during 24 hour period on the dairy sampled during 24-hour period on the dairy | **2:** Not available

Biomethane potential testing

Table 22 shows BMP of composite samples for each sampling event. The biomethane potential of the separator inlet, midpoint, and outlet are generally the same, as seen in the summer and winter seasons. However, BMP data from the spring season deviates from this trend with biomethane potential of the inlet lower than the midpoint and outlet in the spring. Generally, separator solids have a lower biomethane potential than either of the liquid streams; however, data from the summer sampling deviates from this trend, with coarse solids biomethane potential higher than all but the midpoint potential. Figure 28 shows the biomethane potential of Dairy B's separator inlet, midpoint outlet, and coarse (solids pile 1) and fine (solids pile 2) solids biomethane potential test data from different seasons.

Table 22. Dairy B: Biomethane potential (mL/g[VS]) of separator system inlet, midpoint, outlet, and solids 1 and 2 in different seasons

Sample	**Summer** August 2017	**Fall**	**Winter** Dec 2018	**Spring** June 2018
Inlet	185.0 ± 6.4[1]	NA[2]	219.4 ± 9.1	195.1 ± 4.7
Midpoint	198.0 ± 0.0	NA	208.1 ± 0.6	246.1 ± 2.9
Outlet	178.5 ± 9.5	NA	216.9 ± 0.3	239.1 ± 1.5
Solids 1	191.8 ± 22.0	NA	171.7 ± 6.8	120.1 ± 0.0
Solids 2	160.7 ± 9.4	NA	167.7 ± 8.6	113.4 ± 3.1

1: Average values ± standard deviation between two duplicate reactors

2: Not available

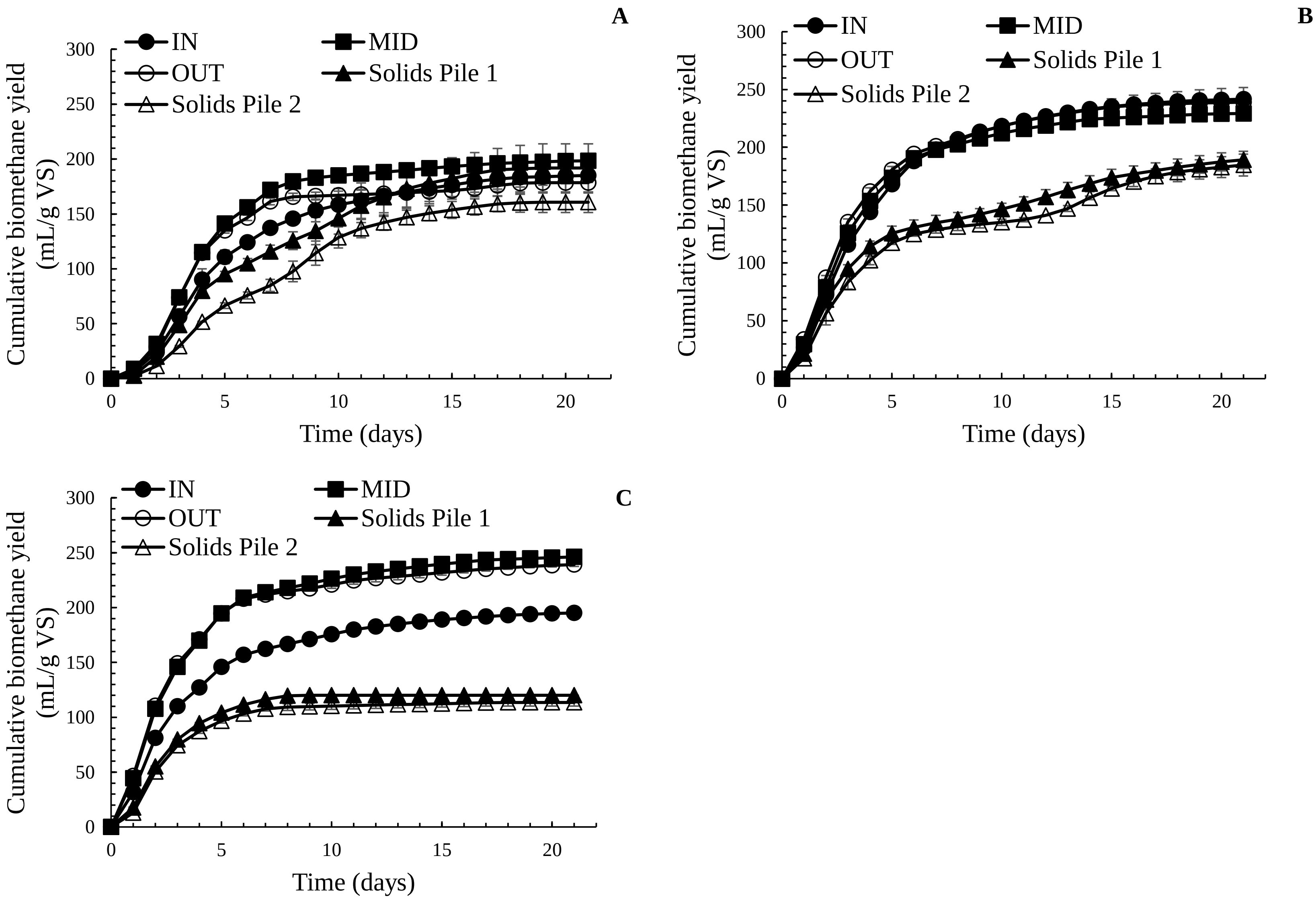

Figure 28. Dairy B: Cumulative biomethane yield in different seasons. **A:** Summer; **B:** Fall; **C:** Spring. Y error bars are standard deviations

Particle size distribution analysis

Figure 29 shows the particle size distribution of composite flushed manure on Dairy B in the Spring quarter. The particles sizes of ⩾ 1mm; < 1mm and ⩾ 500μm; < 500 μm and >250μm, and < 250 μm and ≥75μm represented 27.5%, 10.8%, 9.8%, and 13.5%, respectively. The particle sizes of < 75 μm represented 38.3% of the TS.

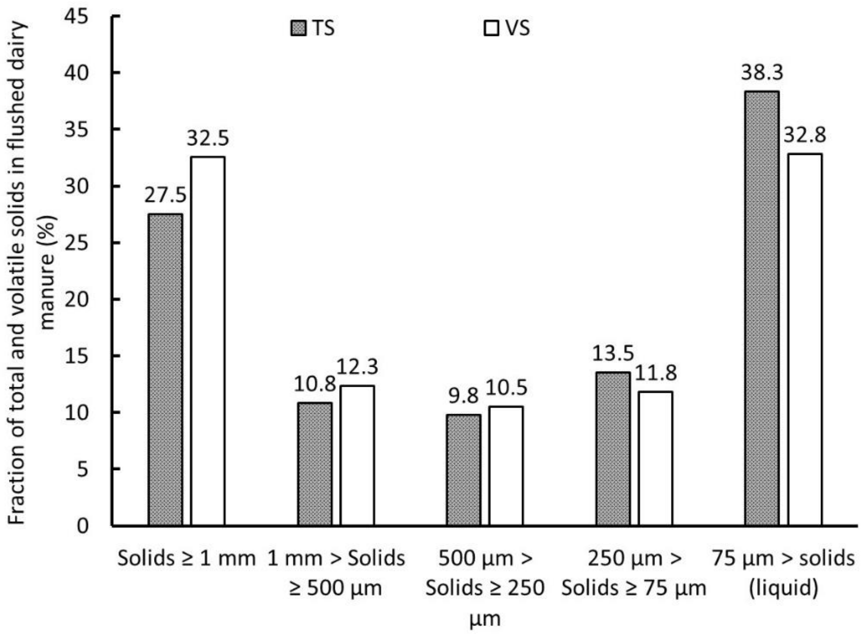

Figure 29. Particle size distribution of the flushed manure on Dairy B

Nutrient analysis

The nutrients concentration in liquid and solid streams for Dairy B are shown in the appendices Tables B3 and B4. The removal efficiency of selected nutrients for the three studied seasons are shown in Table 23. As can be seen the average removal efficiency of N, P, K, Na, and Mg were 19.97%, 26.77%, 7.93%, 6.85%, and 27.83%, respectively. The highest removal efficiencies of the majority of the selected nutrients were achieved during the summer season. Similar to Dairy A, the lowest efficiencies for the removal of Na, and K might be attributed to the fact that they are soluble in the liquid and could not be separated over the separator screens.

Table 23. Removal efficiencies (%, of the separator inlet) of selected nutrients for Dairy B.

Element	Summer	Winter	Spring	Average
Nitrogen	32.74	16.34	10.84	20.0
Phosphorus	44.28	25.19	10.83	26.8
Potassium	8.37	9.95	5.47	7.9
Sodium	6.93	9.08	4.53	6.9
Magnesium	42.89	23.05	17.54	27.8

Dairy B separator solids removal efficiency and methane potential reduction

Table 24 shows separator performance for Dairy B's 1st and 2nd stage, and full system separator in different season. The first stage separator on Dairy B agrees well with its twin separator on Dairy A (Table 17). Fine separator performance data is based on the overall system inlet, which is the same as the 1st stage separator inlet. Values in parenthesis are solid removal efficiencies based on the second stage inlet (Table 24). TS and VS removal efficiency and methane potential reduction for the separation system in the summer season were 60.2%, 64.8%, and 66.0% respectively. TS and VS removal efficiency and methane potential reduction for the separation system in the winter season were 59.8%, 72.8%, and 73.1% respectively. TS and VS removal efficiency and methane potential reduction for the separation system in the spring season were 37.6%, 41.4%, and 28.2% respectively. The regression analysis for the data of the first stage showed a strong negative correlation (R^2 = 0.899) between the separator efficiency and inflow rate: a lower separator efficiency was obtained at lower inflow rate. While there was a weak negative correlation (R^2 = 0.0004) between the separator efficiency and inlet TS.

Table 24. Dairy B: Total and volatile solids removal efficiencies (%) and methane potential reduction (%) in different seasons

Parameter	Stage	**Summer** Aug 2017	**Winter** Dec 2017	**Spring** June 2018	**Average**
TS removal efficiency	1st stage	52.0	59.4	33.5	48.3
	2nd stage	8.2 (12.2[1])	0.5	4.1	4.3
	Full system	60.2	59.8	37.6	52.5
VS removal efficiency	1st stage	57.3	72.3	38.0	55.9
	2nd stage	7.5 (12.9[1])	0.5	3.5	3.8
	Full system	64.8	72.8	41.4	59.7
CH_4 potential reduction	1st stage	54.2	73.8	21.7	49.9
	2nd stage	11.8	-0.6	6.5	5.9
	Full system	66.0	73.1	28.2	55.8

1: Separator performance based on second stage inlet |

Dairy C: Advanced multistage separator

Dairy C description: dairy operation, manure management, flush cycle, and separator

Dairy C is a 2,400 head milking cow facility with five main barns and no exercise pens, indicating that approximately 100% of the manure ends up in the manure flush system. The five freestall bars are 600 feet long and lanes are flushed with about 2,000 gallons/minute for between 5-7 minutes. This dairy has been in operation for approximately 10-15 years at this location. The dairy has approximately 1,050 acres of land. Only 300-350 acres are lagoon accessible and are fertilized by lagoon water. Another 700-750 acres is offsite and is not accessible by the lagoon. Solids from the secondary separator are transported, land applied, and provide the fertilizer for crop cultivation on these acres. No outside fertilizers are used by dairy C except occasional starter applications. Crop rotations include corn, oats, and sorghum. This dairy also employs moisture sensors in the soil to improve irrigation efficiency. Finally, this dairy has a one Mega Watt solar-photovoltaic system to offset most of its electricity costs. Dairy C employs a flush manure management system. Figure 30 depicts the dairy with process flow streams numbered for identification. Points 3, 4, 7, 8, A, and B (1st stage inlet, 1st stage outlet, 2nd stage inlet, 2nd stage outlet, coarse and fine solids) were the primary sampling points where detailed analyses and methane yields from samples were tested. Other sampling points represent secondary sampling points of interest for spot-testing only.

In November 2014, this dairy replaced its old mechanical solid-liquid separator, a scraped screen type, with a new advanced multistage solid-liquid separation system (Figures 31 and 32), one of the only ones like it in California. The system employs rotary drum separators equipped with a roller press for further solids dewatering (Figure 33). It has 2 stages of rotary drum separators, a coarse (primary) and fine (secondary) stage. The separators are designed with perforated drums. The primary separators have 0.125-inch (3,175 µm) round holes. The secondary separators have 0.021 inch (533 µm) square holes. The coarse and fine separators, though physically located next to one another, are separated in terms of the process by a 240,000 gallon settling tank. The settling tank is split into 5 levels. Flush water is pulled from the top 3 levels of the settling tank. This recycled water is used to flush the barns in three separate flush cycles (Figure 30, flow 1). Unlike most other dairies in this study, which flush separate lanes back to back, the flushing of each lane is separated by an 8-10 minute delay. The flushing of the lanes is spread out over 5.5-7.5 hours during each of the three 8-hour flush cycles, depending on the particular flush. According to the dairymen, the timing of these flushes makes a significant difference in the efficiency of their system because it spreads the water out over a longer period of time, allowing for lower flowrates. Lower flow rates allow more time for solids to settle in the settling tank. Flush water is pumped over to a common reception box, where it is agitated (flow 2). The flush water is then processed by 2 coarse separators (Figure 30, flow 3 and Figures 31 and 32), which operate in parallel. Separated solids from the first stage accumulate on a concrete pad below the separators (Figure 30, flow A). Processed flush water from the first stage enters a narrow vertical tank that is designed for sand removal (flow 4). The valve at the bottom of the sand removal tank periodically opens to purge accumulated sand. The remaining water enters into the top of the settling tank (flow 5). Water from the 2 lowest levels of the settling tank has concentrated dairy manure solids. Fine sludge in the bottom of the settling tank gravity discharges through a set of 10-inch PVC pipes with 2-inch perforated holes into another holding tank (flow 6) where it is then pumped to the second stage, 3 fine separators operating in parallel (flow 7). Separated secondary solids collect on a pad below the separators (flow B) and water travels into an earthen settling pond (flow 8) before traveling to one of two lagoons (flow 9). The earthen settling pond is cleaned out about twice a year, down from the four times a year required with the old separator system.

The system has a sophisticated monitoring system, equipped with digital displays that monitor levels in the reception pit, settling tank, and various other locations in the system. The system can also be remotely monitored by mobile application. The accumulated coarse solids (Figure 34) are composted (Figure 35) and either used as bedding (Figure 36) or given to neighbors for use in their almond orchards. According to the owner, composted dairy manure solids have found to be superior to synthetic alternatives because of the organic matter and the increased water holding capacity that they imbue to soils on orchards. Fine solids (Figure 34) from the second stage separator are applied on Dairy C's own fields.

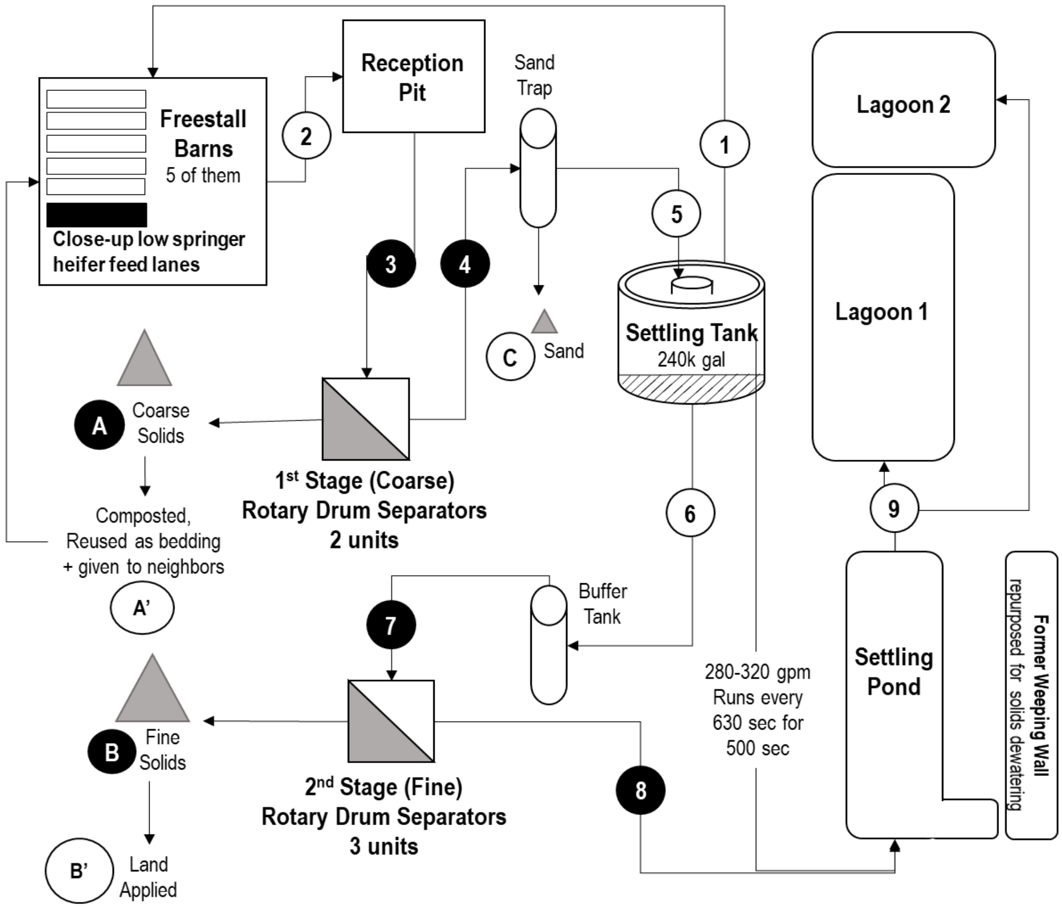

Figure 30. Dairy C: Manure management system diagram
(**3:** 1st stage inlet; **4:** 1st stage outlet; **7:** 2nd stage inlet; **8:** 2nd stage outlet;
A: coarse solids; and **B:** fine solids were sampled streams)

Figure 31. Dairy C: Front view of advanced separation system

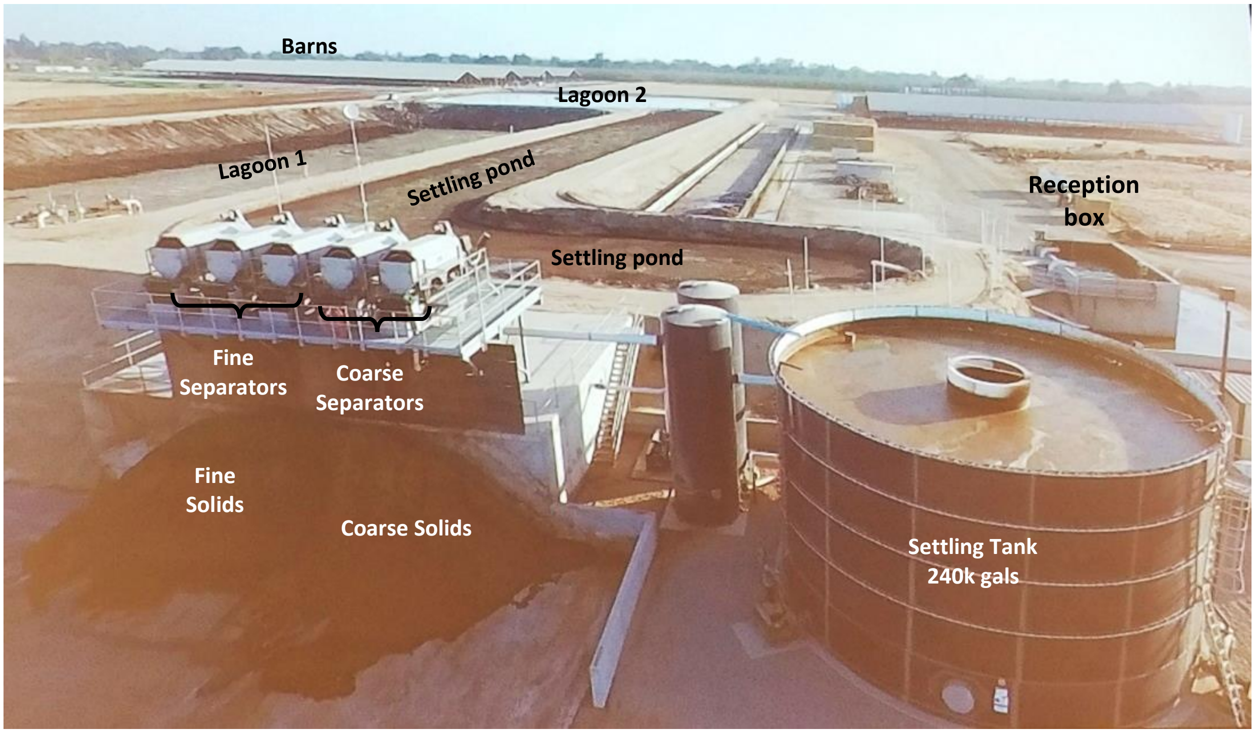

Figure 32. Dairy C: Overhead view of advanced separation system

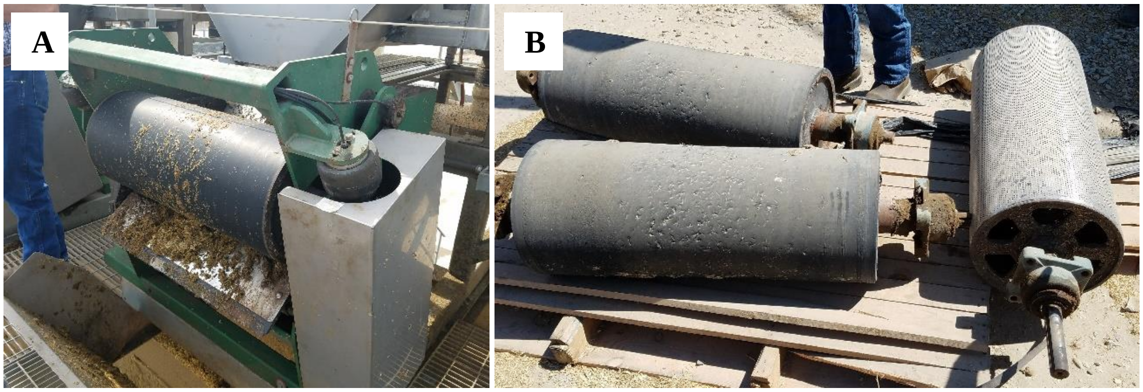

Figure 33. Dairy C: **(A)** Rotary drum separator, and
(B) Separator roller press and rotary drum

Figure 34. Dairy C: Fine (left) and coarse (right) separated solids

Figure 35. Dairy C: Composting operations

Figure 36. Dairy C: Aged bedding pile

Dairy C sampling event description: dates, sampling period and frequency, and weather

Table 25 lists the sampling dates in the summer, winter, and spring seasons at Dairy C.

Table 25. Dairy C: Sampling dates, periods, and frequencies

Season	Date	Sampling period	Sampling frequency
Summer	Aug 15th, 2017	24 hours	30-60 mins
Fall	Nov 29th, 2017	6 hours	15-30 mins
Winter	March 19th, 2018	6 hours	15-20 mins
Spring	June 7th, 2018	6 hours	15-20 mins

Dairy C results: Inflow, TS-VS, pH, methane potential, particle size and nutrient analysis

Separator operation and inflow data

The separator was evaluated over 24 hours during the summer and 6 hours in the fall, winter, and spring. Figures 37, 38, 39, and 40 show the inflow of flush manure to the separator in different seasons. Inflow rate is indicated the left axis and shown in grey while total inflow passing through the separator is indicated on the right axis and shown in black.

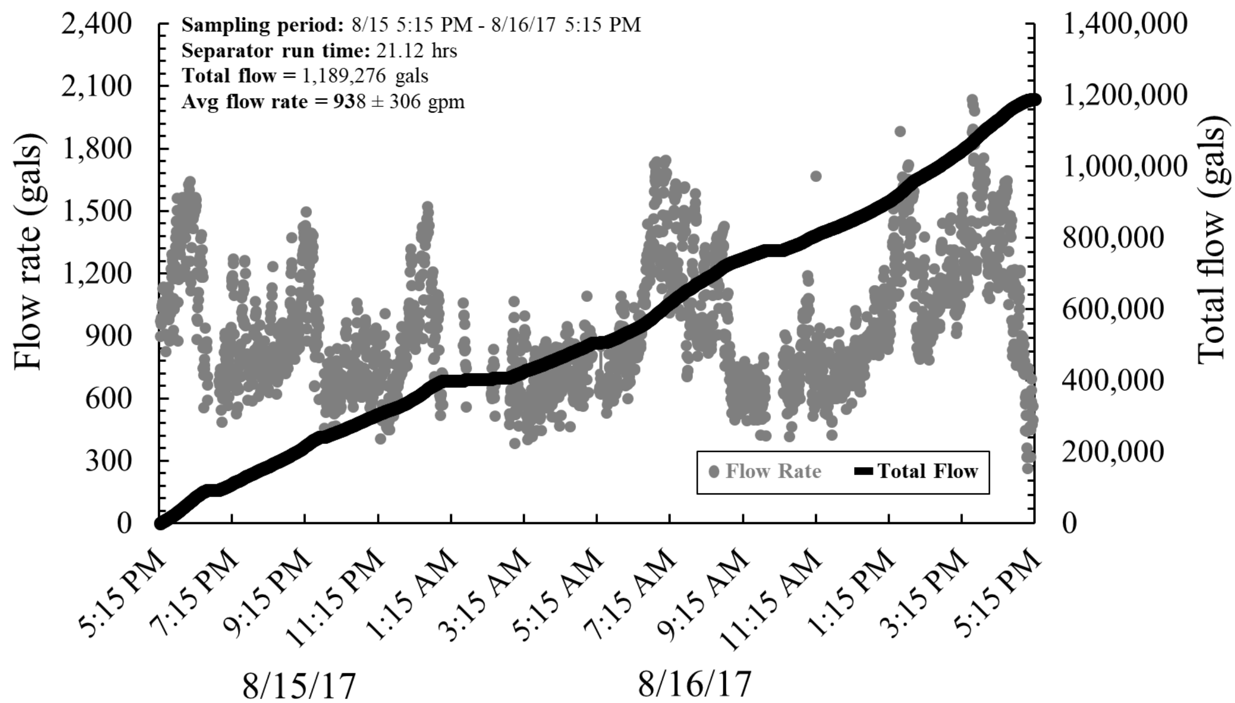

Figure 37. Dairy C: 1st stage, coarse separator summer flow data

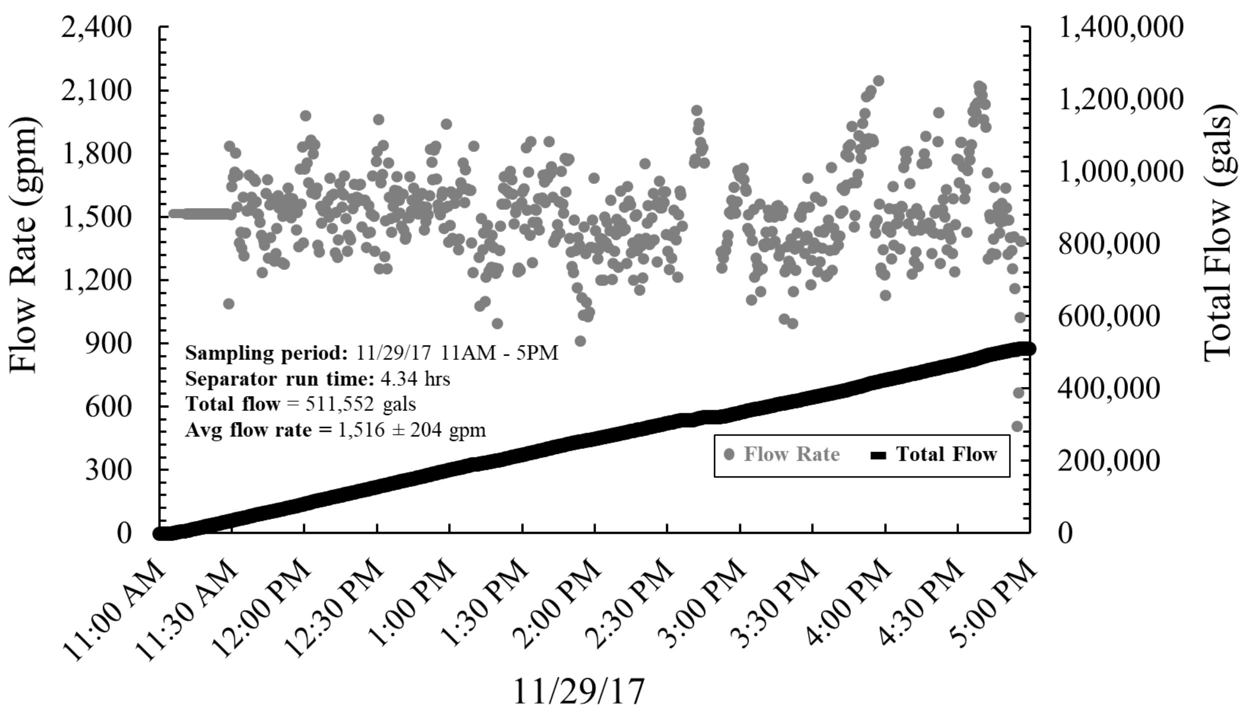

Figure 38. Dairy C: Manure inflow rate and cumulative manure for 1st stage (coarse separator) in the fall

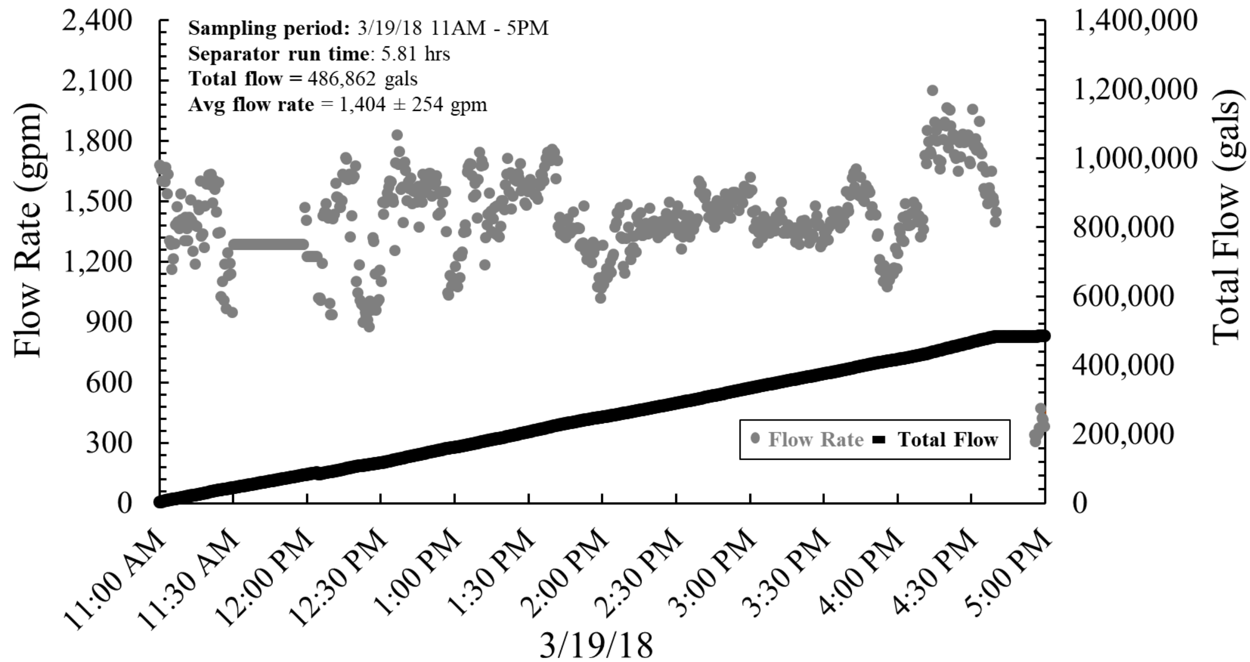

Figure 39. Dairy C: Manure inflow rate and cumulative manure for 1st stage (coarse separator) in the winter

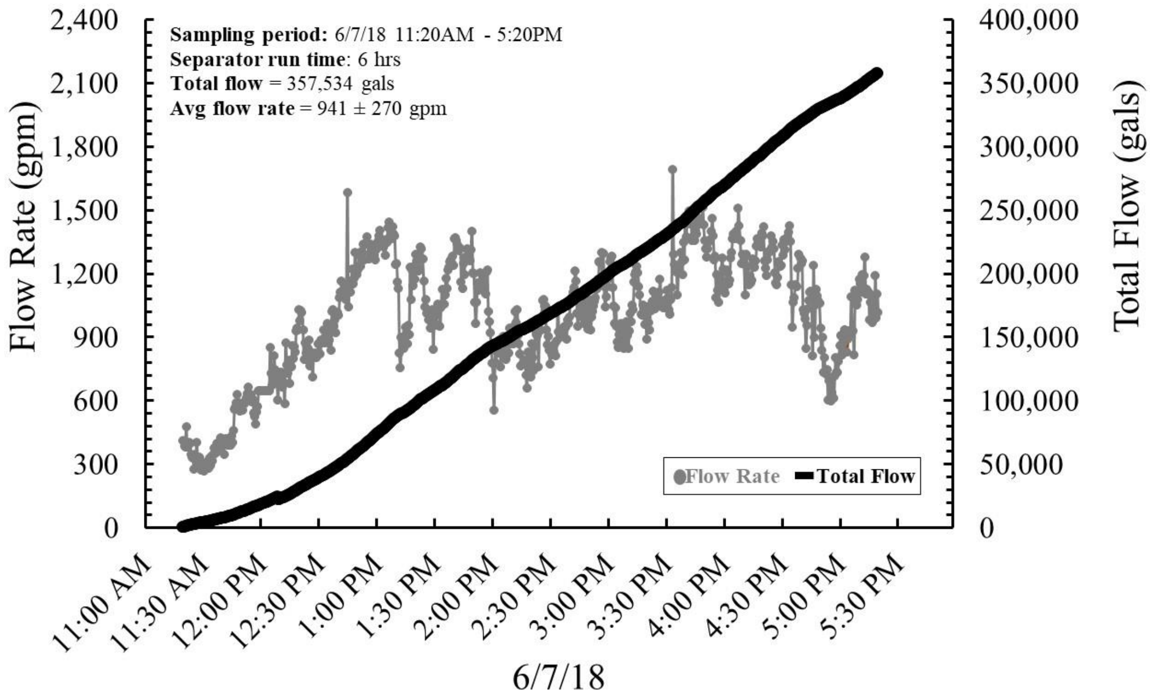

Figure 40. Dairy C: Manure inflow rate and cumulative manure for 1st stage (coarse separator) in the spring

Table 26 summarizes the 1st and 2nd stage, coarse separator operation during each sampling event at Dairy C. The total inflow of manure that enters the first stage was 1,189,276, 511,552, 486,862, and 357,534 gallons in the summer, fall, winter, and spring, respectively. The inflow rate in the summer season was lower (938 ± 306 gpm) than that in the fall (1,516 ± 204gpm), winter (1,404 ± 254 gpm), and spring (999±286 gpm). For comparison, the fine separators operated for 3.51 hours per 6 hours period in the summer sampling event compared to 3.30 hours in the winter. The fine separators processed 62,975 gallons on average per 6 hours in the summer, compared to 75,128 gallons in the winter. The inflow rate for the fine separator is set by the dairy manager and he changed it from 300 gpm in the summer to 380 gpm in the winter, reflecting the need to process more water in this season.

Table 26. Dairy C: 1st stage (coarse separator) and 2nd stage (fine separator) inflow data in different seasons

Parameter	Stage	Summer August 2017	Fall Nov 2017	Winter March 2018	Spring June 2018
Sampling period	System	24	6	6	6
Operating time (hrs)	1st stage	21.12	5.63	5.81	6
	2nd stage	14.02	NA[1]	3.30	3.22
Total inflow (gals)	1st stage	1,189,276	511,552	486,862	357,534
	2nd stage	251,900	NA	75,128	70,755
Inflow rate, average (gpm)	1st stage	938 ± 306[2]	1,516 ± 204	1,404 ± 254	999 ± 286
	2nd stage	300[3]	NA	380[3]	365[3]
Solids (lbs, w.b.)	1st stage	57,700	22,740	19,660	21,260
	2nd stage	104,810	31,360	37,700	29,540

1: Not determined
2: Standard deviation
3: Pump to the second stage separators set at 300 gpm

Total and Volatile Solids, and pH

Table 27 shows total solids and volatile solids concentration (%) and pH of the coarse separator (S1) inlet and outlet, fine separator (S2) inlet and outlet, and coarse (S1) and fine (S2) solids in different seasons. The coarse separator (S1) inlet is equal or lower in pH than the outlet. The fine separator (S2) inlet is lower in pH than the outlet and both are lower in pH than the coarse separator liquid streams. The pH of the coarse (S1) solids is generally greater than the fine (S2) solids and both are higher in pH than the liquid streams; the exception being the summer sampling event. The pH of the coarse solids is higher than the fine solids and both are lower than the liquid streams.

Table 27. Dairy C: Total and volatile solids concentration and pH of separator 1 (S1) inlet and outlet, separator 2 (S2) inlet and outlet, and S1 and S2 solids in different seasons

Sample	Parameter	Summer August 2017	Fall Nov 2017	Winter March 2018	Spring June 2018
S1 Inlet	TS	1.49 ± 0.16[1]	1.63 ± 0.07[3]	1.88 ± 0.18[1]	1.86 ± 0.13[1]
	VS	0.92 ± 0.10[1]	1.12 ± 0.03[3]	1.36 ± 0.13[1]	1.26 ± 0.06[1]
	pH	7.5	7.4	7.0	7.2
S1 Outlet	TS	1.42[2]	1.60 ± 0.03[3]	1.79[2]	1.71
	VS	0.82[2]	1.06 ± 0.01[3]	1.27[2]	1.13
	pH	7.5	7.4	7.1	7.3

S2 Inlet	TS	3.54 ± 0.86[3]	3.64 ± 0.03[3]	3.59 ± 0.60[3]	4.20 ± 0.44[3]
	VS	2.28 ± 0.58[3]	2.51 ± 0.07[3]	2.63 ± 0.43[3]	3.01 ±0.31[3]
	pH	7.2	7.4	6.5	6.7
S2 Outlet	TS	2.65 ± 0.64[3]	2.00 ± 0.05[3]	2.25 ± 0.08[3]	2.74 ± 0.13[3]
	VS	1.30 ± 0.32[3]	1.26 ± 0.00[3]	1.38 ± 0.04[3]	1.43 ±0.03[3]
	pH	7.4	7.5	6.9	7.1
S1 Solids	TS	23.47 ± 1.76	20.88 ± 0.30	22.96 ± 0.47	22.44 ± 0.98
	VS	20.79 ± 1.45	18.46 ± 0.27	21.13 ± 0.55	19.93 ± 0.74
	pH	7.1	7.9	8.0	7.7
S2 Solids	TS	22.11 ± 0.65	21.21 ± 0.04	21.03 ± 0.19	19.60 ± 0.20
	VS	16.97 ± 0.33	16.68 ± 0.07	17.08 ± 0.07	14.81 ± 0.16
	pH	7.0	8.1	8.0	7.8

1: $TS_{S1\text{-}Inlet}$ calculated by interpolated measured sample TS and accounting for inflow data
2: $TS_{S1\text{-}Outlet} = TS_{S1\text{-}Inlet} - S1_{Solids}$ | **3**: Based on TS of collected samples | **4**: Not Determined because of the lack of inflow data

Biomethane potential testing

Table 28 depicts BMP of composite samples for each sampling event. The coarse separator inlet (S1 inlet) and outlet (S1 outlet), generally have about the same biomethane potential, higher than of any samples across all seasons, except for the summer season when the coarse separator outlet was lower. The fine separator inlet (S2 inlet) and outlet (S2 outlet) have about the same biomethane potentials in the summer season; however, the outlet has higher potential for the other three seasons. The solids generally have the lowest biomethane potential with the coarse being the lowest, followed by the fine solids. In the summer, winter, and spring seasons, the highest biomethane potential was obtained for the inlet of the first stage. In the fall season, the highest biomethane potential was obtained for the outlet of the first stage.

Figure 41 shows the biomethane potential over the incubation time for Dairy C's coarse separator (S1) inlet and outlet, fine separator (S2) inlet and outlet, and coarse (solids pile 1) and fine (solids pile 2) solids biomethane potential test data from different seasons. Table 28 shows biomethane potential after 21 days.

Table 28. Dairy C: Biomethane potential (mL/g[VS]) of separator 1 (S1) inlet and outlet, separator 2 (S2) inlet and outlet, and S1 and S2 solids in different seasons

Sample	**Summer** August 2017	**Fall** Nov 2017	**Winter** March 2018	**Spring** June 2018
S1 Inlet	237.8 ± 3.1[1]	276.4 ± 6.1	275.1 ± 0.3	263.4 ± 8.9
S1 Outlet	197.2 ± 9.4	282.3 ± 5.7	255.1 ± 8.7	261.1 ± 0.0
S2 Inlet	192.8 ± 3.2	228.4 ± 3.3	204.1 ± 10.9	189.8 ± 5.1
S2 Outlet	201.8 ± 3.3	262.9 ± 0.1	224.1 ± 2.3	219.0 ± 0.8
S1 Solids	140.7 ± 17.6	180.1 ± 6.5	122.1 ± 2.9	160.0 ± 3.9
S2 Solids	152.7 ± 3.2	193.3 ± 1.1	154.2 ± 3.1	171.5 ± 0.0

1: Average values ± standard deviation between two duplicate reactors

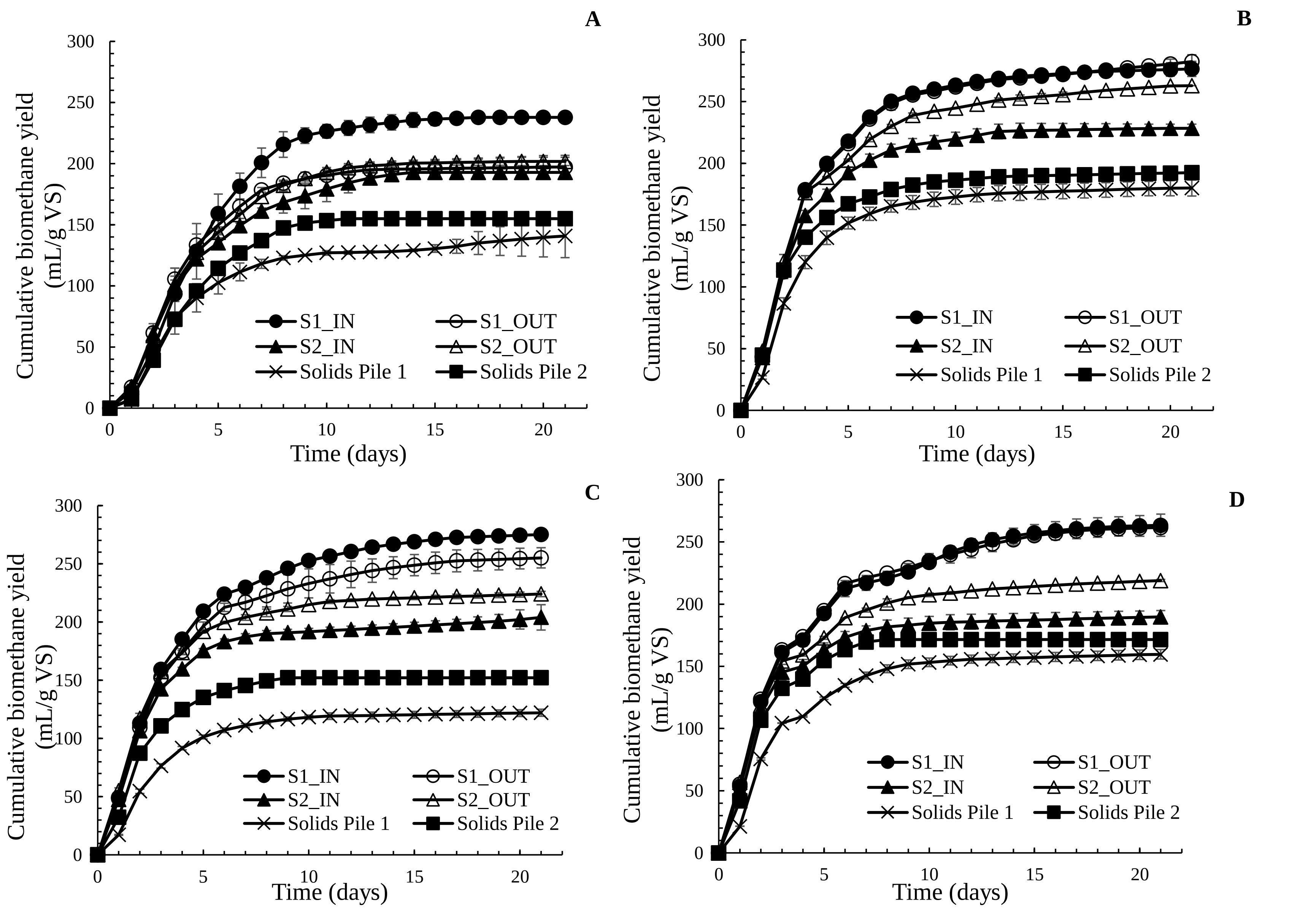

Figure 41. Dairy C: Cumulative biomethane yield in different seasons. **A:** Summer; **B:** Fall; **C:** Winter; **D:** Spring. Y error bars are standard deviations

Particle size distribution analysis

Two influent streams were analyzed separately for the advanced separator system because the two stages work independently as described in the description of the separation system (Figure 42 and 43). The solids in the flushed manure entering the first stage rotary screen separators were more consistent than that entering the second stage. In the influent to the first stage coarse solid separation, the particle sizes of ≥ 1mm, < 1mm and ≥ 500μm; < 500 μm and ≥250μm; and < 250 μm and ≥ 75μm represented 14.8%, 10.3%, 7.7%, and 10.6% of the TS, respectively. After sand removal and sedimentation in the settling tank (in the influent to the second stage fine solids separation), the particle sizes of ≥ 1mm, < 1mm and ≥ 500μm; < 500 μm and ≥250μm; and < 250 μm and ≥ 75μm represented 35.1%, 10.5%, 9.8%, and 14.1%, respectively.

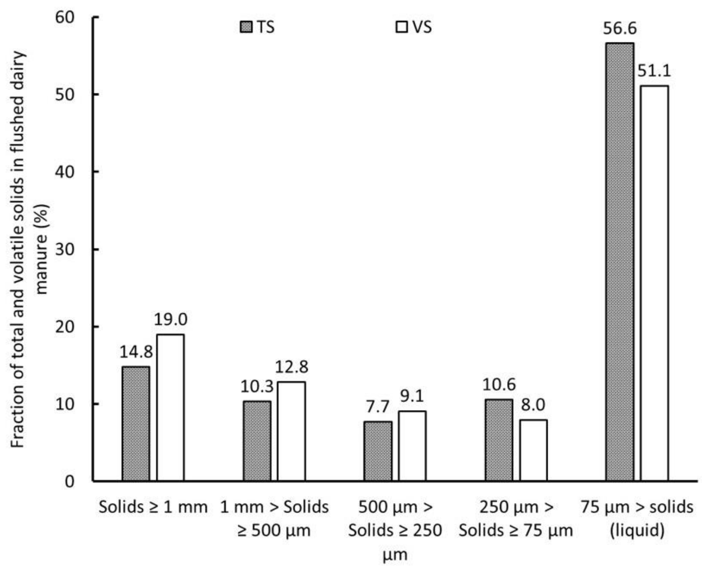

Figure 42. Particle size distribution of the flushed manure entering the first stage of the separator system on Dairy C

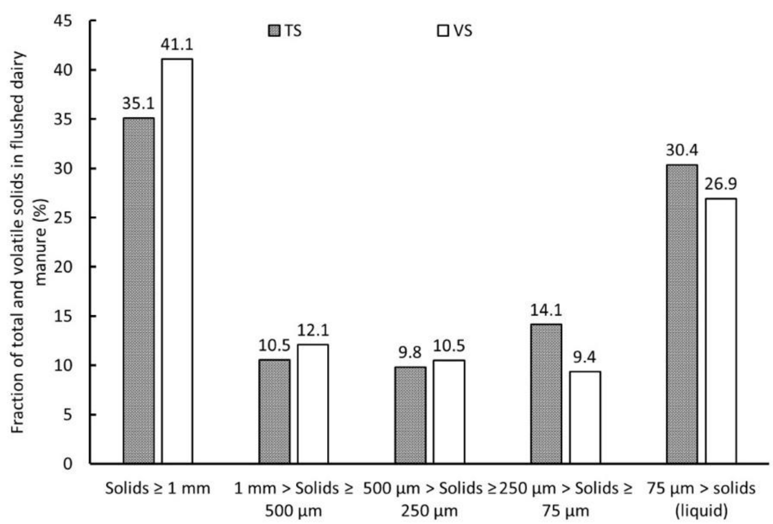

Figure 43. Particle size distribution of the flushed manure entering the second stage of the separator system on Dairy C

Nutrient analysis

The nutrients concentration in liquid and solid streams for Dairy C are shown in the appendices Tables B5 and B6. The removal efficiency of selected nutrients for the three studied seasons are shown in Table 29. As can be seen the average removal efficiency of N, P, K, Na, and Mg were 5.93%, 6.80%, 1.67%, 1.39%, and 7.99%, respectively. The highest removal efficiencies of N, P, and Mg were achieved during the summer season. Similar to other dairies, the low efficiencies were determined for the removal of Na, and K. Since the daily separated solids may be exported out of the dairy, the calculated removal efficiencies of the selected elements were calculated as percentages of that of the inlet of the first separator. The nutrients concentrations in the recirculated wastewater for manure flushing were not considered in the calculations.

Table 29. Removal efficiencies (%, of the separator inlet) of selected nutrients for Dairy C.

Element	Summer	Winter	Spring	Average
Nitrogen	9.46	5.07	3.25	5.9
Phosphorus	13.27	4.31	2.83	6.8
Potassium	1.57	1.72	1.72	1.7
Sodium	1.24	1.48	1.44	1.4
Magnesium	13.43	4.65	5.87	8.0

Dairy C separator solids removal efficiency and methane potential reduction

Table 30 shows separator performance data for Dairy C's 1st and 2nd stage separator in different seasons. The coarse separator solids removal efficiency is relatively low, which is not surprising given that the screen size of the first stage separators are 3.175 mm (Table 2). The regression analysis for the data of the first stage showed a strong negative correlation ($R^2 = 1.00$) between the separator efficiency and inflow rate. While there was a negative correlation ($R^2 = 0.399$) between the separator efficiency and inlet TS. The second stage, fine separators remove much more solids (Table 27), possessing 533 µm screens. The highest removal efficiencies of TS and VS removal and the CH_4 potential reduction, were obtained during the winter time. They were 78.8%, 79.6%, and 83.4% respectively. It should be mentioned that large portion of the VS is removed through the settling tank probably due to the biological degradation or recirculated with the flush water. The regression analysis for the data of the second stage showed a weak negative correlation ($R^2 = 0.031$) between the separator efficiency and inflow rate. While there was a strong negative correlation ($R^2 = 0.945$) between the separator efficiency and inlet TS. Further, the determined high efficiencies of TS and VS removals and the CH_4 potential reduction is due to the fact that this farm recirculates 20%-25% of the flush water for flushing the barns. This recirculated water is processed through the first stage. Again, more data collection is needed to derive a multiple correlation between the separator efficiency and the both of the inflow rate and the inlet TS.

Table 30. Dairy C: 1st stage, coarse separator solids removal efficiencies and methane potential reduction in different seasons

Parameter	**Stage**	**Summer** Aug 2017	**Winter** Mar 2018	**Spring** June 2018	**Average**
TS removal efficiency	1st stage	9.1[1]	5.8[1]	8.7	7.9
	Settling Tank	40.5[1]	62.8[1]	44.8	49.4
	2nd stage	15.5[1] (30.8[2])	10.2[1] (32.5[2])	10.6[1] (23.1[2])	12.10 (28.8)
	Full system	65.1[1]	78.8[1]	64.2	69.4
VS removal efficiency	1st stage	12.9[1]	7.4[1]	11.5	10.6
	Settling Tank	34.8[1]	60.7[1]	39.3	44.9
	2nd stage	19.2[1] (36.7[2])	11.5[1] (36.1[2])	11.9[1] (24.4[2])	14.2 (32.4)
	Full system	66.9[1]	79.6[1]	62.7	69.7
CH_4 potential reduction	1st stage	27.8[1]	14.1	14.1	18.7
	2nd stage	31.4[1] (33.8[2])	27.9[1] (32.7[2])	n.d.[3]	n.d.[3]
	Full system	71.9[1]	83.4[1]	69.0	74.8

1: Calculated based on 1st stage inlet | **2:** Calculated based on 2nd stage inlet | **3:** Not determined

Dairy D: 1-stage horizontal scraped-screen separator

Dairy D description: dairy operation, manure management, flush cycle, and separator

Dairy D is a 750 head milking cow facility with another 750 in dry cows and heifers. The dairy has been operating since 1971 and houses Jersey cows. Milk is used exclusively for cheese production. Figure 44 depicts the dairy with process flow streams numbered for identification. The samples collected at the points 3, 4, and 5 (separator inlet, outlet, and solids) were analyzed and used for methane yields tests. Other samples were collected for spot-testing only.

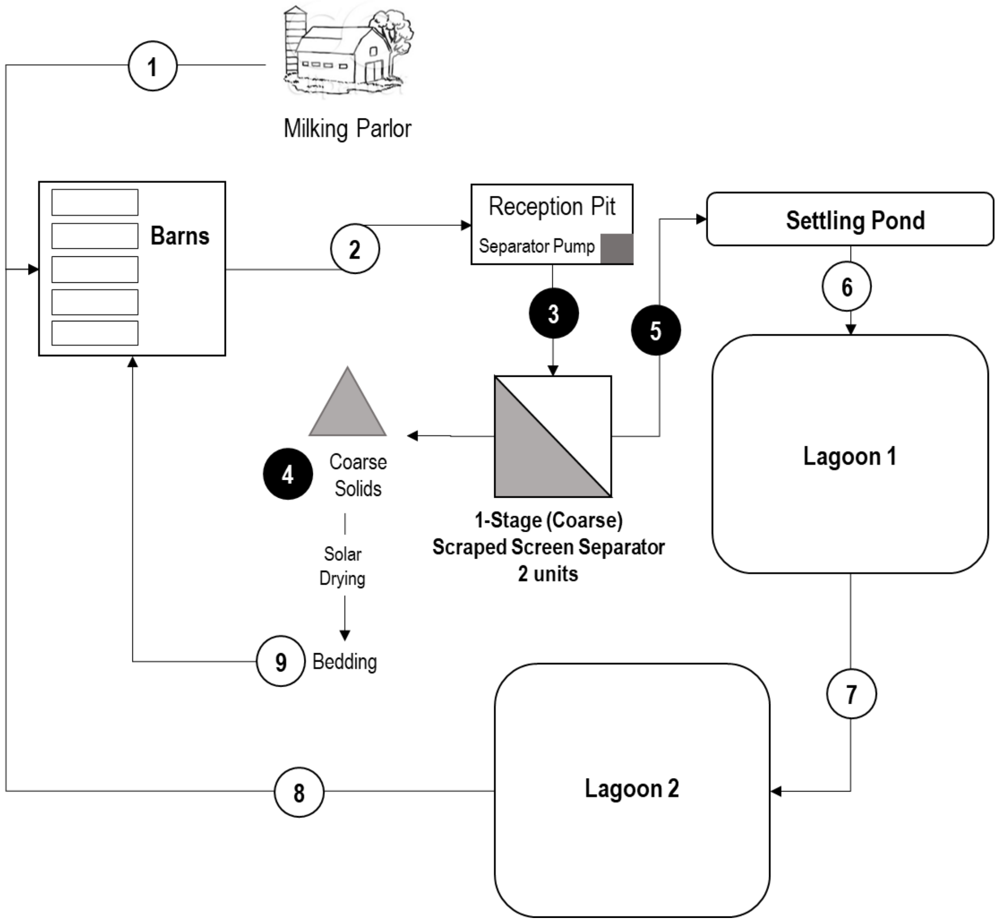

Figure 44. Dairy D: Manure management system diagram
(**3:** separator inlet, **4:** separator outlet; and **5:** separator solids were sampled streams)

Flush water is drawn from a combination of lagoon and milk parlor process water. The process water from the milk parlor is stored in a tall, 20,000 gallons cylindrical tank and discharged about twice daily. Lagoon water is pumped from lagoon two into the barns (Figure 44, flow 8). Flush water travels to a small processing pit, with an agitator pump situated in a corner of the pit (flow 2). This pump is activated by a level sensor. The single pump is not able to properly mix the water in the pit, which is why the solids concentration immediately at the beginning and end of each separator run is significantly higher than during the rest of the separator operating period. To increase the mixing in the pit, at least one more pump is needed. Water is transferred from the pit over to two horizontal scraped screen separators that operate in parallel (flow 3). Separated solids are collected on a concrete pad (flow 4) while processed water flows through the screens and out into a settling pond before it travels into a series of 2 lagoons (flows 5, 6, and 7). Although the two separators are designed to handle about 500-800 gallons per minute each, according to the manufacturer, the water pumped over to them at this dairy is, for periods of time, more than they can process. The separators are designed such that extra water by passes the separator by flowing over the screens into a pipe that send the water directly to the settling pond. Separated solids are stored in large piles during the cool months. During the warm weather months, they are spread on concrete pads, solar dried, and prepared as bedding.

The flush schedule is broken up into 4 programs. Two of those programs (A and B) flush 4 freestall barns housing milking cows. A fifth freestall barn was not flushed directly, rather it is continuously flushed because all the flush water must pass through it to get to the reception pit. The other two other programs (C and D) are dedicated to flushing 1 pen each, housing heifers and dry cows. Programs A and B are run 3 times a day, while C and D are run twice a day. Flushing occurs only in the day from 5 AM until about 4 PM. Manure accumulates in the barns overnight without being flushed, resulting in the early flush water having higher solids content than at the end of the day. Additionally, process and wash water from the milking parlor is discharged twice a day (6 AM and 6 PM) at milking. The flush programs and schedules are detailed in the following two tables (Tables 31 and 32).

Table 31. Dairy D: Flush programs

Program	Cow Type	Pens	Valves	Flush time	Start time
A	Milking	1+3	1-4	5, 5, 7, 7 = 24 mins total	5AM, 9AM, 2PM
B	Milking	2+4	5-8	7, 7, 5, 5 = 24 mins total	6AM, 10AM, 3PM
C	Heifer/Dry	NA	9-14	2, 2, 2, 3, 2, 3 = 14 mins total	7AM, 11AM
D	Heifer/Dry	NA	15-20	2, 4, 2, 3, 2, 2 = 15 mins total	8AM, 12:30PM

Table 32. Dairy D: Flush sequence

Flush	Program	Cow Type	Pens	Valve	Flush time/valve and total	Start time
1	A	Milking	1+3	1-4	5, 5, 7, 7 = 24 mins total	5:00 AM
1	B	Milking	2+4	5-8	7, 7, 5, 5 = 24 mins total	6:00 AM
1	C	Heifer/Dry	NA	9-14	2, 2, 2, 3, 2, 3 = 14 mins total	7:00 AM
1	D	Heifer Dry	NA	15-20	2, 4, 2, 3, 2, 2 = 15 mins total	8:00 AM
2	A	Milking	1+3	1-4	5, 5, 7, 7 = 24 total	9:00 AM
2	B	Milking	2+4	5-8	7, 7, 5, 5 = 24 total	10:00 AM
2	C	Heifer/Dry	NA	9-14	2, 2, 2, 3, 2, 3 = 14 mins total	11:00 AM
2	D	Heifer Dry	NA	15-20	2, 4, 2, 3, 2, 2 = 15 mins total	12:30 AM
3	A	Milking	1+3	1-4	5, 5, 7, 7 = 24 total	2:00 PM
3	B	Milking	2+4	5-8	7’, 7’, 5’, 5’ = 24’ total	3:00 PM

The separator system at Dairy D is a 1-stage scraped screen separator (Figures 45 and 46). The manufacturer of this separator offers two and single stage systems. The first stage is designed for coarse solids removal and has a screen with 18-gauge perforate holes (3/32 inches or 2.38 mm in diameter). Unlike the sloped separator type, the screens on the scraped system have holes rather than slits. The second stage removes finer solids and has a screen with 22-gauge (0.05 inches or 1.27 mm) holes. Dairy D only has a one stage system.

Water entering the separator flows over the horizontal screens, following a carousel-like oval shaped route. Scrapers move the solids over the screen to the end of the separator where a roller press further dewaters the solids before they land onto a concrete pad (Figure 45). In the original design (prior to this study), the first several feet of screen that comes into contact with flush water is actually the same screen as that employed in the second stage system (22 gauge, 1.27 mm perforated holes); however, the company servicing the separator finds this screen is susceptible to failure and must frequently be replaced. To overcome these issues, they have replaced with a uniform 18-gauge screen.

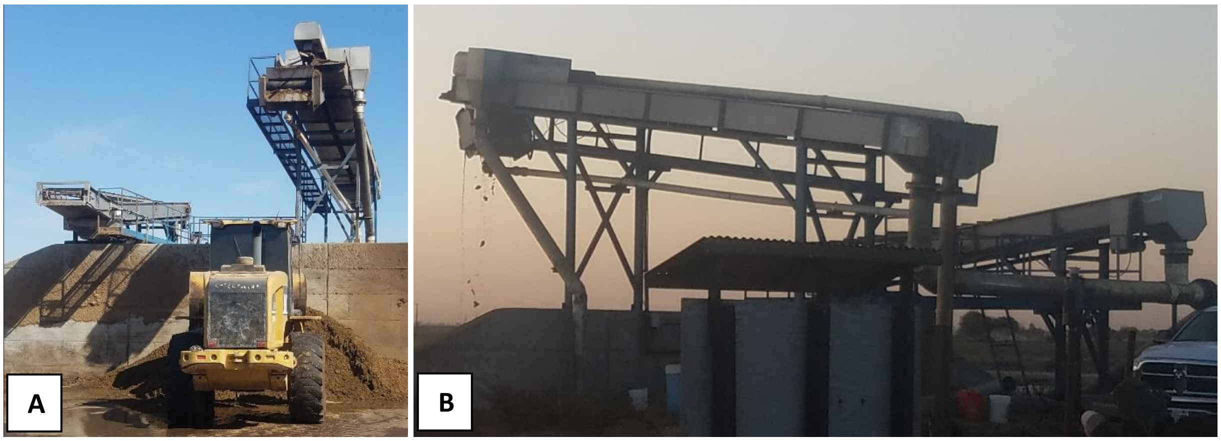

Figure 45. Dairy D*: **(A)** Front and **(B)** Rear view of horizontal scrape-screen separator

Figure 46. Dairy D*: Scraped screen separator in action

Dairy D sampling event description: dates, sampling period and frequency, and weather

Table 33 lists the sampling dates in the summer, winter, and spring seasons at Dairy D.

Table 33. Dairy D: Sampling dates, periods, and frequencies

Season	Date	Sampling period	Sampling frequency
Fall (Dairy D*, data not analyzed)	Oct 3rd, 2017	24 hours	30 mins
Winter	March 11th, 2018	24 hours	5-20 mins
Spring	June 12th, 2018	24 hours	5-20 mins
Summer	Sept 5th, 2018	8 hours	5-15 mins

Dairy D results: Inflow data, TS-VS, pH, methane potential, particle size distribution and nutrient analysis

Separator operation and inflow data

The separator was evaluated over 24 hours during the winter and spring sampling events and 8 hours in the summer. The fall sampling event took place at the original Dairy D* site, but data was not analyzed when it was discovered that the pipes on this dairy were full of deposits. These deposits affect the accuracy of the inflow measurements and therefore determination of separator efficiency and methane potential reduction were infeasible. Figures 47 and 48 show the inflow of flush manure to the separator in different seasons. Inflow rate is indicated on the left axis and shown in grey while total inflow passing through the separator is indicated on the right axis and shown in black.

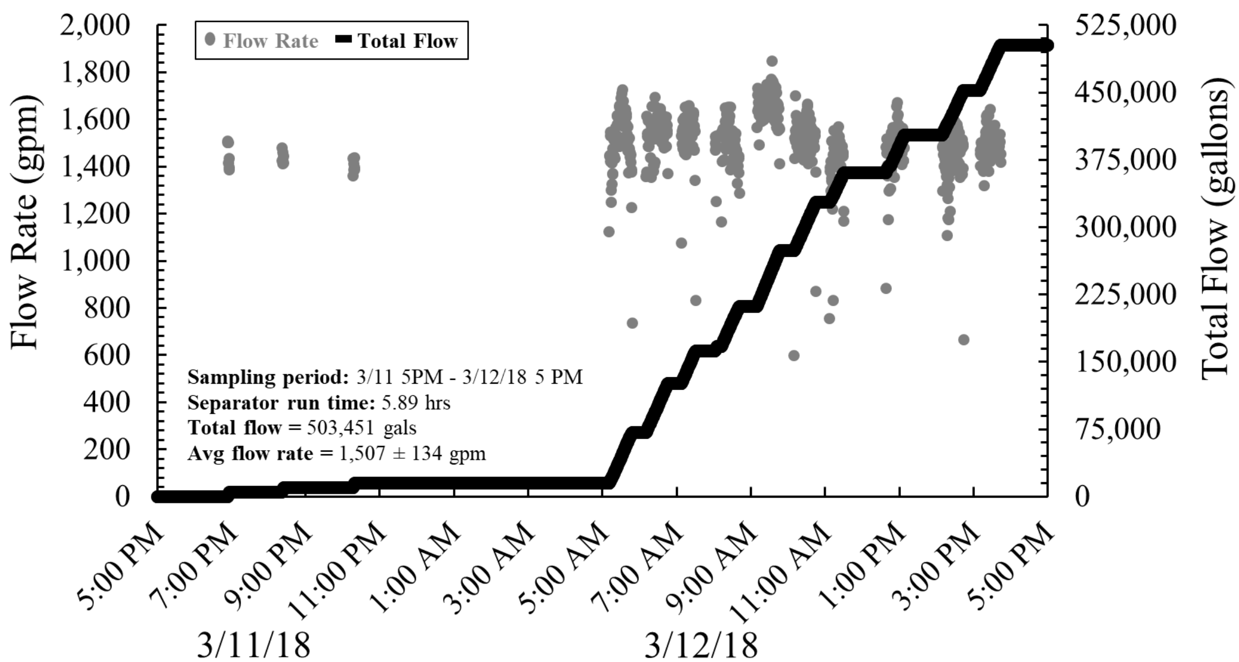

Figure 47. Dairy D: Manure inflow rate and cumulative manure in the winter

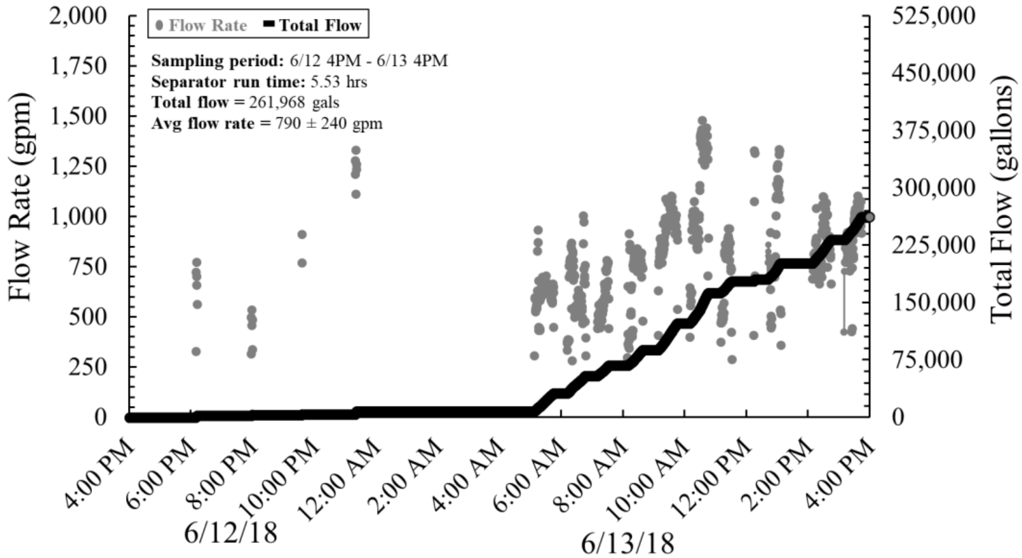

Figure 48. Dairy D: Manure inflow rate and cumulative manure in the spring

Table 34 summarizes separator operation during each sampling event at Dairy D. During the winter season sampling, a significant overflow of the separator was observed at the beginning and end of each time the separator turned on and off. This was because the reception pit feeding the separator is small and not well mixed. Solids concentration spikes for the first several minutes when the separator turns on and again just before it turns off because the separator pump pulls concentrated settled solids from the bottom of the reception pit. The result was that an undetermined amount of inflow passed over the separator. When this happens, the separator has an overflow pipe to divert excess, unprocessed flush manure directly into the lagoon. This excess flow decreased separator performance numbers because the project team could not differentiate between what flow was processed by the separator versus what flowed unprocessed into the lagoon.

In the spring and summer sampling events, the project team slowed down flow from the separator pump and diverted excess flow from the reception pit to the lagoon prior to the separator. The goal was to provide the separator with a flow that it could handle to evaluate performance under more ideal conditions. These modifications explain differences in separator flow data between winter and spring seasons. The total inflow to the separator in the summer was 242,704 gallons, and in the winter (503,451 gallons) was almost double that of the spring (261,968 gallons). Inflow rate was also about double in the winter (1,507 ± 134 gpm) compared to the spring season (790 ± 241 gpm), although the separator operating time remained unchanged.

Table 34. Dairy D: Separator inflow data in different seasons

Parameter	**Units**	**Summer** Sep 2018	**Winter** March 2018	**Spring** June 2018
Sampling period	hrs	8	24	24
Operating time	hrs	3.1	5.57	5.53
Total inflow	gals	242,704	503,451	261,968
Inflow rate, average	gpm	1,277 ± 218	1,507 ± 134	790 ± 241
Solids	lbs, wb	10,420	19,020	13,440

Total and Volatile Solids, and pH

Table 35 shows total and volatile solids concentration and pH of separator inlet, outlet, and solids in different seasons, respectively. The separator inlet pH is consistently the lowest followed by the outlet, and solids.

Table 35. Dairy D: Total and volatile solids concentration (%) and pH of separator inlet, outlet, and solids in different seasons

Sample	Parameter	**Summer** Sep 2018	**Fall** Oct 2017	**Winter** March 2018	**Spring** June 2018
Inlet	TS	1.47 ± 0.04	n.d.[1]	1.72 ± 0.31	1.56 ± 0.30
	VS	0.90 ± 0.04	n.d.[1]	1.14 ± 0.26	0.95 ± 0.26
	pH	7.4	n.d.[1]	7.7	7.6
Outlet	TS	1.12 ± 0.01	n.d.[1]	1.60 ± 0.17	1.37 ± 0.11
	VS	0.60 ± 0.01	n.d.[1]	1.04 ± 0.13	0.78 ± 0.08
	pH	7.6	n.d.[1]	7.7	7.8
Solids	TS	20.22 ± 1.67	n.d.[1]	17.00 ± 1.40	19.86 ± 1.15
	VS	17.96 ± 1.47	n.d.[1]	15.65 ± 1.34	18.08 ± 1.16
	pH	n.d.[1]	n.d.[1]	8.3	8.4

1: Not determined, Dairy D* sampling

Biomethane potential testing

Table 36 shows BMP of composite samples for each sampling event. Figure 49 shows the biomethane potential of Dairy D's separator inlet, outlet, and solids from two seasons. The highest and lowest biomethane potential was obtained for the outlet and solids streams in the spring season.

Table 36. Dairy D: Biomethane potential (mL/gVS) of separator inlet, outlet, and solids in different seasons

Sample	**Summer** Sep 2018	**Fall** Oct 2017	**Winter** March 2018	**Spring** June 2018
Inlet	140.25 ± 6.15[1]	n.d.[2]	n.d.	154.7 ± 12.7
Outlet	152.58 ± 3.48	n.d.	n.d.	161.2 ± 1.3
Solids	128.18 ± 3.15	n.d.	n.d.	122.7 ± 10.5

1: Average values ± standard deviation between two duplicate reactors

2: Not determined

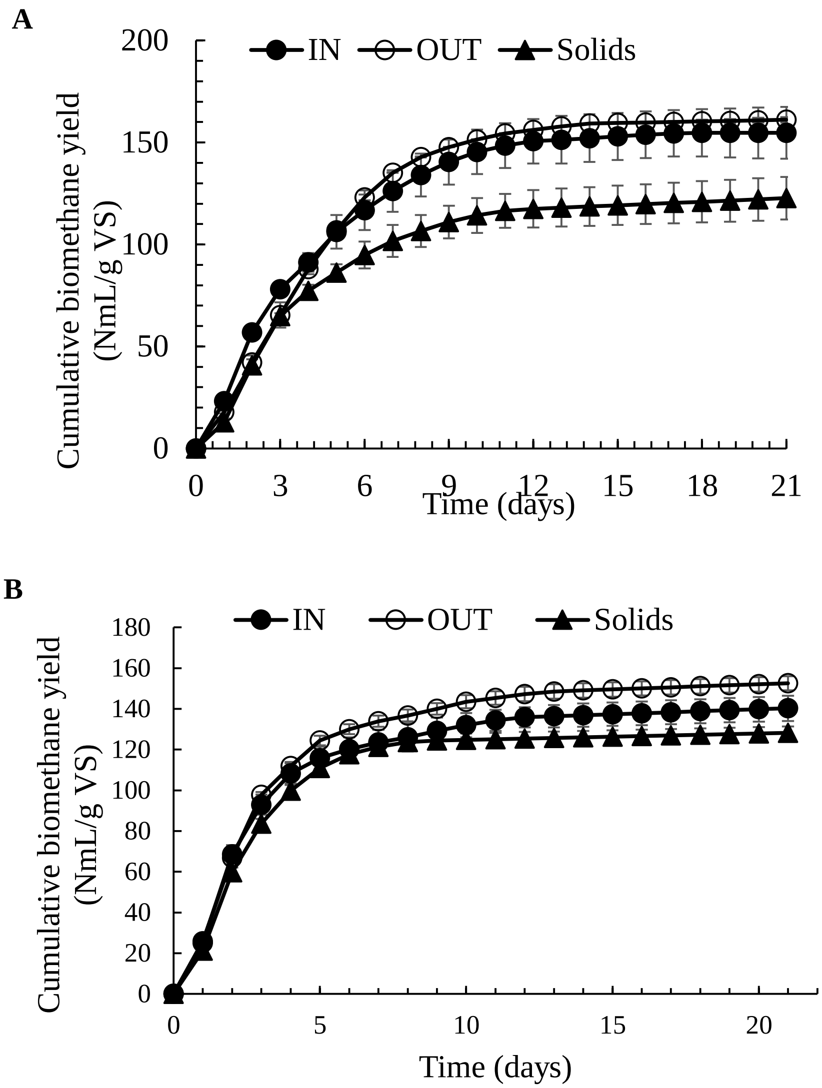

Figure 49. Dairy D: Cumulative biomethane yield in different seasons. A: Spring; B: Summer. Y error bars are standard deviations

Particle size distribution analysis

Figure 50 shows the particle size distribution of composite flushed manure on Dairy D in the Spring quarter. The particle sizes of ≥ 1mm, < 1mm and ≥ 500μm; < 500 μm and ≥ 250μm; and < 250 μm and ≥ 75μm represented 12.5%, 7.5%, 6.0%, and 8.6% of the TS, respectively. Approximately 65% of the TS was < 75μm and passed the finest screen in the particle size distribution analysis.

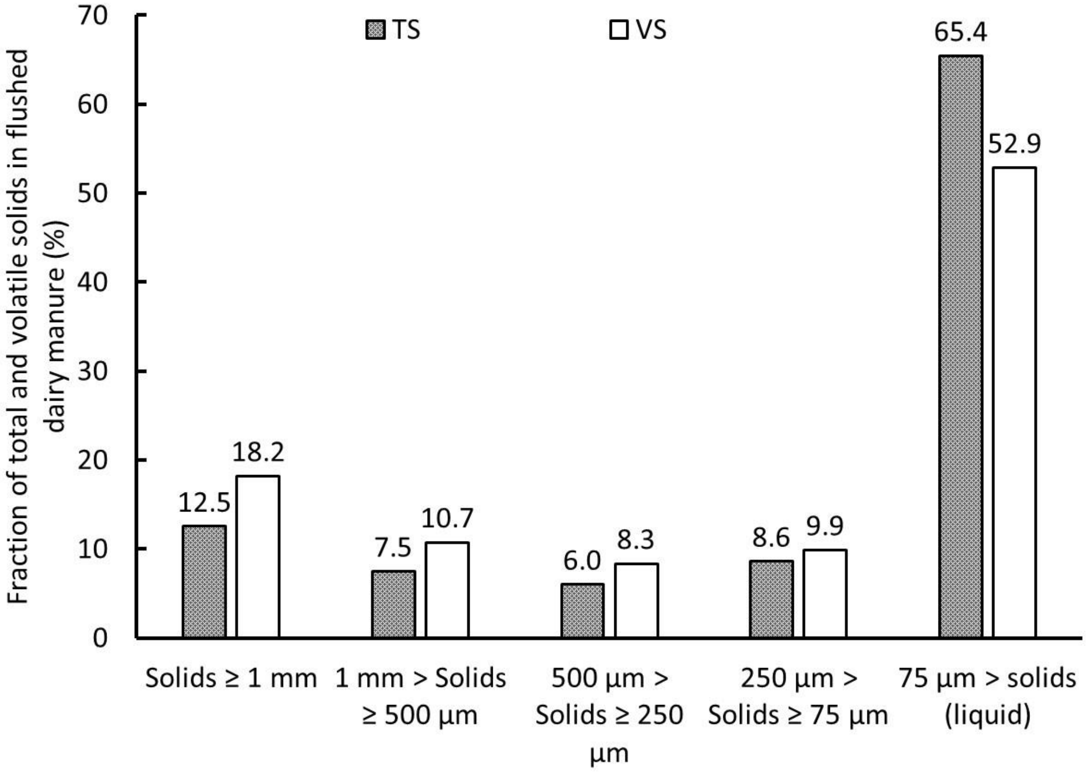

Figure 50. Particle size distribution of the flushed manure on Dairy D

Nutrient analysis

The nutrients concentration in liquid and solid streams for Dairy D are shown in the appendices Tables B7 and B8. The removal efficiency of selected nutrients for two seasons are shown in Table 37. As can be seen the average removal efficiency of N, P, K, Na, and Mg were 0.33%, 0.39%, 0.20%, 0.18%, and 0.51%, respectively. Compared with other studied dairies, very low removal efficiencies of nutrient could be determined.

Table 37. Removal efficiencies (%, of the separator inlet) of selected nutrients for Dairy D

Element	Winter	Spring	Average
Nitrogen	0.55	0.12	0.3
Phosphorus	0.65	0.14	0.4
Potassium	0.33	0.06	0.2
Sodium	0.31	0.06	0.2
Magnesium	0.86	0.16	0.5

Dairy D separator solids removal efficiency and methane potential reduction

Table 38 shows separator performance data for Dairy D's separator in different seasons. Among all the studied mechanical separators, this system had the lowest TS and VS removal efficiency and CH_4 potential reduction. This probably due to the relatively larger screen size in this separator than other screen separators (Table 5). It should be noted that solids removal efficiencies in the winter were about half those in the spring. This could be attributed to the unaccounted for, excess flush manure that flowed to the separator and unprocessed flow, directly into the lagoon. The regression analysis showed a strong negative correlation ($R^2 = 0.966$) between the separator efficiency and inflow rate. While there was a negative correlation ($R^2 = 0.3821$) between the separator efficiency and inlet TS.

Table 38. Dairy D: Separator solids removal efficiencies (%) and methane potential reduction (%) in different seasons

Parameter	**Summer** Sep 2018	**Winter** Mar 2018	**Spring** Jun 2018	**Average**
TS removal efficiency	6.3	4.7	8.0	6.3
VS removal efficiency	9.4	6.5	12.1	9.2
CH_4 potential reduction	1.4	n.d.[1]	8.4	4.9

1: Not determined, Dairy D* sampling

Dairy E: Weeping wall

Dairy E description: dairy operation, manure management, flush cycle, and separator

Dairy E is the site of the weeping wall system. A herd of about 8,000 dairy cows are housed at this site. Unlike other sites, where flush cycles are on a set schedule, at Dairy E the flush program for each barn is initiated manually, once that barn's cows have been moved over to the milking parlor.

Figure 51 depicts the dairy with process flow streams numbered for identification. Samples from points 4, 5, and 6 (weeping wall inlet, outlet, and solids) were taken for primary analyses and for methane yields tests. Other points were secondary sampling points of interest for spot-testing only.

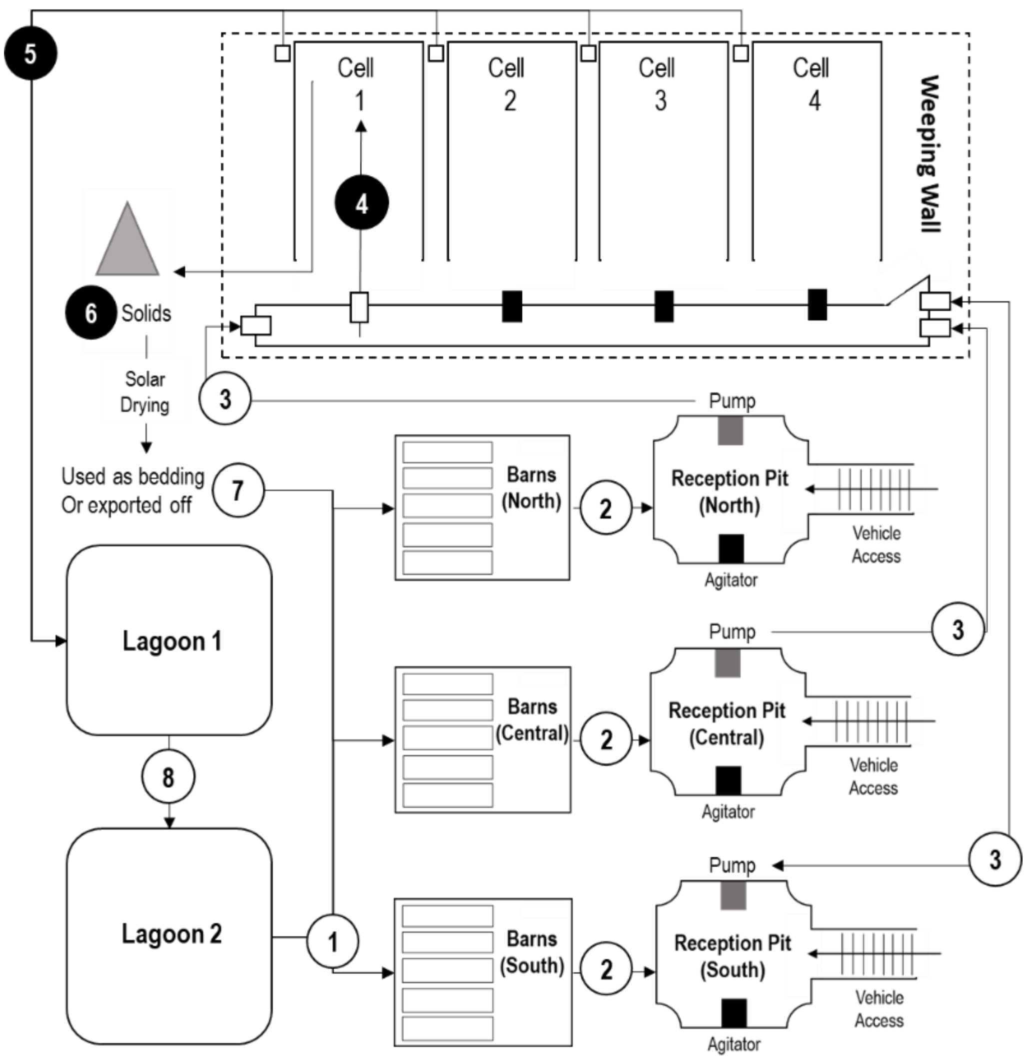

Figure 51. Dairy E: Manure management system process diagram
(**4:** weeping wall inlet; **5:** weeping wall outlet; and **6:** weeping wall solids were sampled streams)

Flush water is sourced from one of the dairy's two lagoons. It is pumped into the dairy's regional barns (Figure 51, flow 1). The dairy is split into North, Central, and South regions. Flushed manure enters into a regional hexagonal processing pit, two of which (North and Central pits) operate on float sensors (flow 2). When a float sensor is activated, flushed manure from the different sides converge at a concrete transfer channel, which directs the flow out of a 24" valve before entering the weeping wall (flow 3 and 4). The South side processing pit is activated manually. It receives excess water entering into the transfer channel. Once per day, as this pit fill, the flush water is pumped out of the pit to the transfer channel and into the weeping wall, similar to flush water from the North and Central regions.

Solids build up in the weeping wall over time and act as a filter. Filtered water flows into a series of 2 lagoons (flow 5 and 6). Solids are solar dried and either used as compost on the dairy or exported off the dairy (flow 7). A third-party company manages the weeping wall, the solids composting operation, and sale of the conditioned solids. Figure 52 shows flush manure receiving wall, 24” valve out of receiving wall, and weeping wall cells.

Figure 52. Dairy E: **(A)** flush manure receiving wall, (**B)** 24” valve out of receiving wall, and **(C)** weeping wall cells, right one filling and left one being emptied.

Dairy E sampling event description: dates, sampling period and frequency, and weather

Table 39 lists the sampling dates for Dairy E.

Table 39. Dairy E: Sampling dates, periods, and frequencies

Season	Cell	Date	Sampling period	Sampling frequency
Summer	1	Sept 18th, 2018	48 hours	1-2 hours
Fall	1	Sept 25th, 2018	48 hours	1-2 hours
Fall	1 / 2	Oct 2nd, 2018	24 hours	1-2 hours
Fall	2	Oct 10th, 2018	24 hours	0.5-2 hours
Fall	2	Oct 18th, 2018	8 hours	1-2 hours

Flow measurements at every dairy thus far has been carried out with a MACE™ doppler insert velocity sensor; however, the flush manure on this dairy flows out of a 24” valve directly into the weeping wall. In order to measure flow on this dairy, a 15 foot 24” PVC pipe was installed on the valve. Because there was no way to ensure a full pipe, which is a requirement for the doppler insert velocity sensor, the project team rented a MACE™ doppler area/velocity sensor from In Situ, Inc. This sensor can take flow measurements from partially filled pipes by measuring velocity and water depth in the pipe. The MACE™ doppler card calculates a cross sectional area of flow based on depth and computes inflow rate by multiplying cross sectional area by velocity data.

The flow meter setup was tested from September 13th – 18th, 2018 to ensure feasibility and accurate measurements of the system. Sampling began immediately thereafter, on two consecutively filled weeping wall cells. The first cell sampling began on September 18, 2018and concluded two weeks later on October 2. The second cell sampling began October 2,2018 and concluded on October 20, 2018.

Dairy E results: Inflow data, TS/VS, pH, methane potential, particle size distribution and nutrient analysis

Separator operation and inflow data

The weeping wall system was evaluated for two cells. Inflow data was recorded throughout the whole filling period. Figures 53 and 54 show the cumulative amounts and the inflow rate of the flush manure for cell 2 and cell 1 of the weeping wall, respectively.

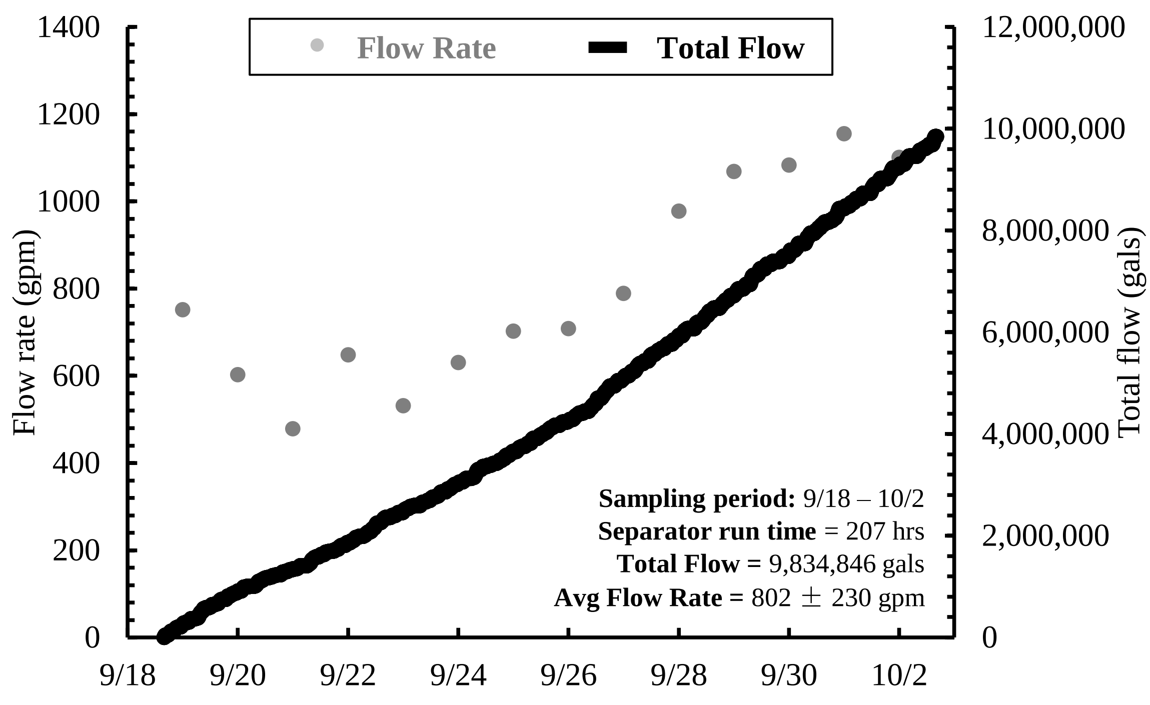

Figure 53. Cumulative manure inflow for the Cell No. 2 on dairy E

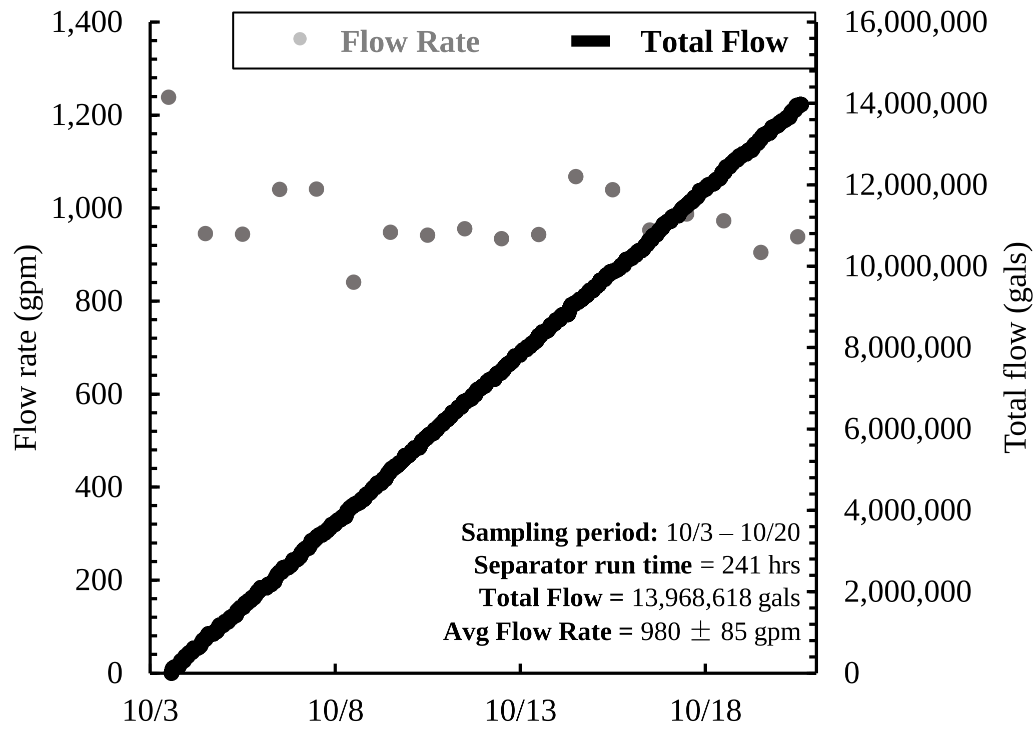

Figure 54. Cumulative manure inflow for the Cell No. 1 on dairy E

Table 40 summarizes weeping wall operation and sampling period during the sampling events of the Cell No. 2 and Cell No. 1 at dairy E. The filling times were 14, and 18 days, and the cells emptying times were 6 and 7 days, respectively. The total inflow of manure was 9,834,846, and 13,968,618 gallons for the cell No. 2 and No. 1, respectively. The operating time (manure flow times to the cells) were 207, and 241 hours, respectively. The total mass of solids removed was 5,805,900, and 8,724,130 lbs wet basis, respectively. It should be mentioned that, the mass weight for cell No. 1 was missed for one day. Therefore, we averaged the solid weight in the previous and the following day and took this average as the mass of the solids in the missed day's weight. The filling time may slightly vary for different cells depending on the TS contents in the influent, manure inflow rate, and availability of equipment and labor. Also, there may be emissions of $PM_{2.5}$ and NO_x from the loader employed to empty the cells and the trucks used for transportation of the solids to the compost facility that is located at about 0.5 miles from the weeping cells. These emissions should be determined.

Table 40. Dairy E: Separator inflow, weight of solids, and filling times for the two cells

Parameter	**Units**	**Cell 2** Sep 2018	**Cell 1** Oct 2018
Cell filling time	days	14	18
Operating time	hrs	207	241
Total inflow	gals	9,834,846	13,968,618
Cell emptying time	days	6	7
Mass of solids	lbs, wb	5,805,900	8,724,130

Total and Volatile Solids, and pH

Table 41 shows the TS and VS concentration and pH of weeping wall cells inlet, and outlet and solids removed from both cells after the filling periods. As can be seen, the TS and VS concentrations in the liquid streams were comparable for both cells. However, the TS and VS of the solids accumulated in Cell 2 was higher than those of Cell 1. This might be because the solids in Cell 2 were kept without filling in the cell for 34 days as compared to 22 days in the Cell No. 1. The longer holding time in the Cell No. 2 allows more drainage and evaporation of the liquid. The solids were kept longer in Cell 2 because the lack of labor and equipment. Solids in the cell might be a potential source of GHG emissions due to the anaerobic degradation during the filling and drying. Research is needed to determine the CH_4 and NOx emissions from the solids in the cells.

Table 41. Dairy E: Total and volatile solids concentration (%) and pH of separator inlet, outlet, and solids in two different cells

Sample	**Parameter**	**Cell 2** Sep 2018	**Cell 1** Oct 2018
Inlet	TS	1.79 ± 0.12	1.63 ± 0.01
	VS	1.30 ± 0.11	1.19 ± 0.01
	pH	6.9	6.9
Outlet	TS	1.04 ± 0.02	1.10 ± 0.02
	VS	0.73 ± 0.02	0.80 ± 0.02
	pH	6.7	6.7
Solids	TS	26.43 ± 0.94	21.82 ± 0.11
	VS	19.61 ± 0.73	16.68 ± 0.13
	pH	n.d.[2]	n.d.[2]

Figure 55 shows the biomethane potential of Dairy E's separator inlet, outlet, and solids from two cells. Table 42 shows biomethane potential for the liquid and solid streams after 21 days of digestion. The inlet of Cell No. 1 had a relatively higher CH_4 methane potential than cell No.2. The solid streams had very low CH_4 potential. This might be due to the losses of biodegradable VS during the storage inside the weeping wall cells. As can be seen the VS/TS for cell 1 and No. 2 were 74.2% and 76.4%, respectively. It should be mentioned that the actual methane emissions from the weeping wall system may be higher than the determined biomethane potential from the lagoon due to possible methane emissions from the cells during the filling, draining and drying times, as well as the handling and storage of the separated solids. A more detailed study is needed to measure methane emissions from the solids during and post accumulation in the weeping wall cells. It is worth mentioning here that various weeping wall designs might affect solid separation efficiency and water content in the cell. Future research should be conducted to evaluate different designs of weeping walls.

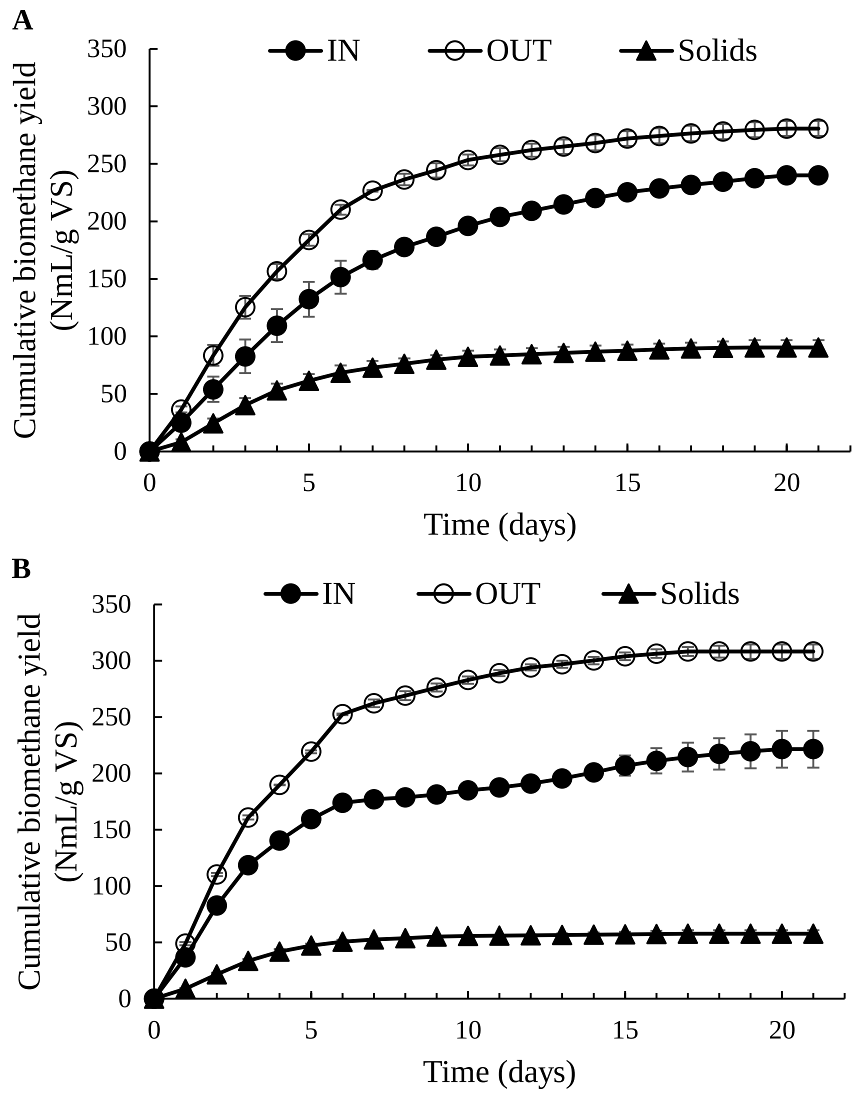

Figure 55. Dairy E: Cumulative biomethane yield in different seasons. A: Cell 1; B: Cell 2

Table 42. Dairy E: Biomethane potential (mL/g[VS]) of separator inlet, outlet, and solids from different cells

Sample	**Cell 2** Sep 2018	**Cell 1** Oct 2018
Inlet	221.50 ± 16.33	240.00 ± 3.22
Outlet	308.05 ± 6.43	280.70 ± 6.58
Solids	57.83 ± 3.01	90.45 ± 6.22

Particle size distribution

Figure 56 shows the particle size distribution of composite flushed manure on Dairy E in the fall. The particles sizes of ≥ 1mm; <1mm and ≥ 500µm; <500 µm and ≥ 250 µm, and < 250µm and ≥75 µm represented 33.1%, 10.9%, 8.5%, and 13.5%, respectively. The particle sizes of < 75µm represented 34.1% of the TS.

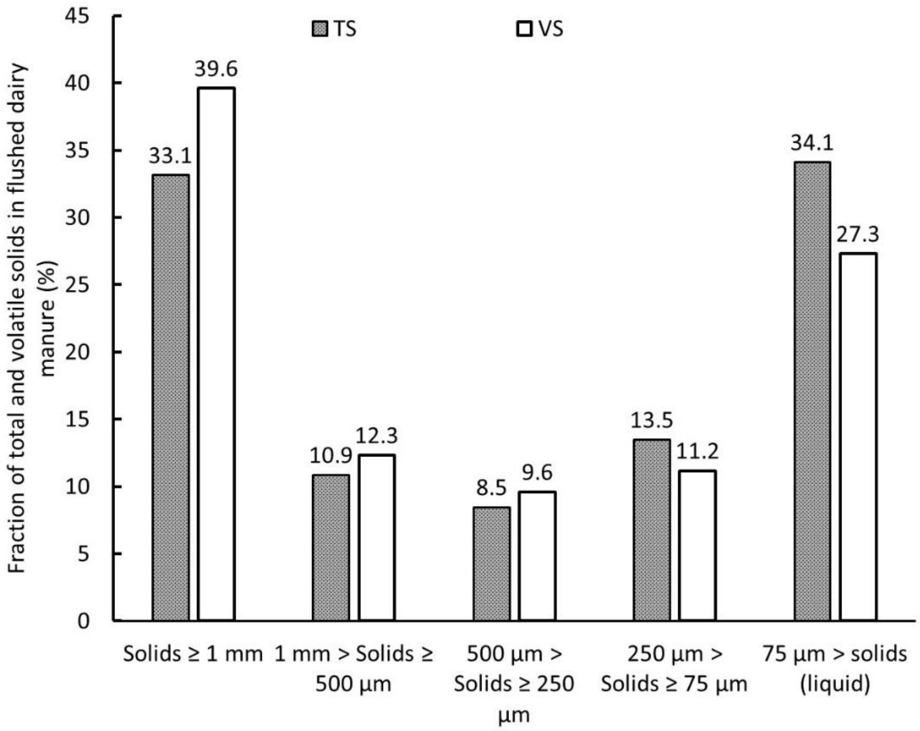

Figure 56. Particle size distribution of the flushed manure on Dairy E

Nutrient analysis

The nutrients concentration in liquid and solid streams for Dairy E for two cells are shown in the appendices Tables B9 and B10. The removal efficiency of selected nutrients for two cells are shown in Table 43. As can be seen the average removal efficiency of N, P, K, Na, and Mg were 23.10%, 27.06%, 10.13%, 7.54%, and 42.99%, respectively. Similar to the other dairies, Na and K had the lowest removal efficiencies.

Table 43. Removal efficiencies (% of the inlet of the weeping wall) of selected nutrients in the two studied cells on Dairy E.

Element	Cell 1	Cell 2	Average
Nitrogen	27.59	18.62	23.1
Phosphorus	31.34	22.78	27.1
Potassium	12.44	7.83	10.1
Sodium	9.02	6.06	7.5
Magnesium	47.48	37.69	42.6

Dairy E separator solids removal efficiency and methane potential reduction

Table 44 shows the removal efficiency of TS, and VS, and the CH_4 potential reduction. The average removal efficiencies of TS and VS, and CH4 potential reduction of both studied cells were 80.15%, 82.55%, and 78.0%, respectively. As can be seen, higher TS and VS removal efficiencies and CH_4 potential reduction could be achieved in Cell No. 2 than Cell No. 1. This may be attributed to the longer storage time in the Cell No.2 as compared with the Cell No.1. The longer holding time might increase the degradation of organic matter during the storage time. Although the higher reduction of CH_4 in the Cell No. 2 (i.e., the larger diversion of methane emissions from the lagoon), it is not clear what is the fate of the degraded VS accumulated in the weeping wall cells. More research is needed to determine the final products of the VS degraded inside the cells. Moreover, as can be seen the accumulated solids in the cells had the lowest biomethane potential. This may indicate that the accumulated solids might be degraded during the filling, draining, and drying times. More research is needed to determine the possible mechanism for the degradation of the organic matter in the weeping wall cells.

Table 44. Dairy E: Separator solids removal efficiencies (%) and methane potential reduction (%) in two different cells

Parameter	**Cell 2** Sep 2018	**Cell 1** Oct 2018	**Average**
TS removal efficiency	81.9	78.4	80.2
VS removal efficiency	86.1	79.0	82.6
CH_4 potential reduction	80.6	75.4	78.0

Dairy F: 1-stage sloped single-screen separator

Dairy F description: dairy operation, manure management, flush cycle, and separator

Dairy F is a 1,850 head milking cow facility with an additional 400 dry cows and 1,700 heifers. This dairy has four freestall barns and several corrals. Dairy F employs a flush manure management system.

Figure 57 depicts the dairy with process flow streams numbered for identification. Samples were taken from points 2a, 3, and 4 (separator inlet, outlet, and solids) for detailed analyses and methane yields tests. Samples were collected from other locations for secondary sampling points of interest for spot-testing only.

Barns are flushed four times a day for 63 minutes each flush. Flush water enters a large earthen processing pit (Figure 57, flow 1; Figure 58) that is approximately 72 feet by 81 feet in size. The pit is equipped with an agitator; a separator pump, which directs flush water to the separator (Figure 57, flow 2a); and a second pump, which can bypass the separator and pump flush water directly to a settling pond (flow 2b) that is roughly the same size as the processing pit. According to the owner, the settling pond is never cleaned out. Manure has dried and formed a solid layer of crust on top of it (Figure 59). Flush water passes from the earthen processing pit to a 1-stage sloped single-screen separator (Figure 57, flow 2a). The screen design is similar to that on Dairies A and B, built with metal slits, except the sloped single screen has three sections rather than two like Dairies A and B (Figure 60). The slit spacing in the top third section is 0.015 inches (381 µm), the middle third is 0.025 inches (635 µm), and the bottom third is 0.035 inches (889 µm). Screened flush water enters the earthen settling pond (Figure 56, flow 4) and then flows into a lagoon (flow 5). Water for flushing the barns is derived from this lagoon (flow 6).

The separator pump and settling pond pump operation are controlled by level sensors in the earthen settling pit. It was noticed that some flush water could bypass the separator directly to settling basin. It is not clear at this time how much of the flush water is processed through the separator and how much bypasses the separator and flows directly to the settling pond. The water bypassed the separator does not affect the calculated efficiency of the separator because the bypassed waster was not used in calculating the separator efficiency. The primary purpose of the separator is to generate solids for use as bedding in the barns. Separated solids are spread out and dried before being stacked into piles and used as bedding either in the freestalls or in corrals.

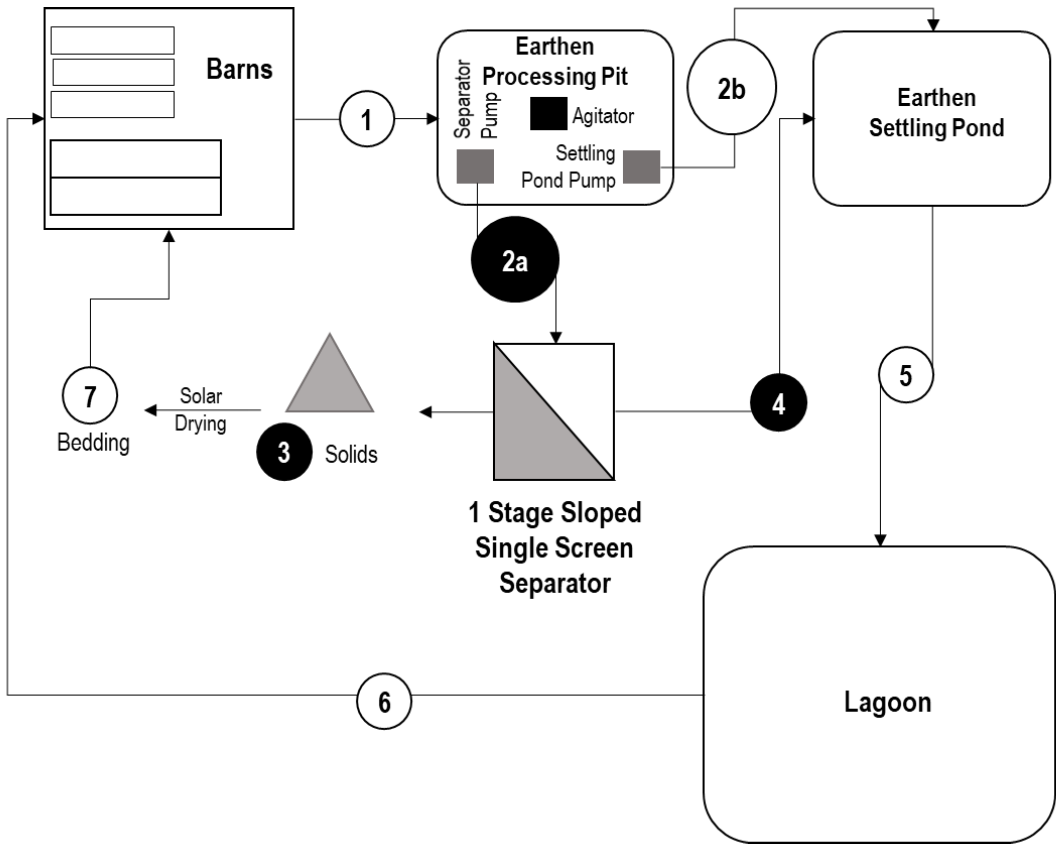

Figure 57. Dairy F: Manure management system diagram
(**2a:** separator inlet; **3:** separator outlet; and **4:** separator solids were sampled streams)

Figure 58. Dairy F: Earthen processing pit

Figure 59. Dairy F: Earthen settling pond

Figure 60. Dairy F: **(A)** separator system and **(B)** system front view

Dairy F sampling event description: dates, sampling period and frequency, and weather

Table 45 lists the sampling dates in the summer, winter, and spring seasons at Dairy F.

Table 45. Dairy F: Sampling dates, periods, and frequencies

Season	Date	Sampling period	Sampling frequency
Fall	Nov 7th, 2017	24 hours	0.5 hours
Winter	March 6th, 2018	24 hours	0.5 hours
Spring	June 8th, 2018	9 hours	0.3-0.75 hours
Summer	Sept 12th, 2018	9 hours	0.5-0.75 hours

Dairy F results: Inflow data, TS-VS, pH, methane potential, particle size and nutrient analysis

Separator operation and inflow data

The separator was evaluated over 24 hours during the fall and winter sampling events and 9 hours in the spring and summer.

Figures 61, 62, 63 and 64 show the inflow of flush manure to the separator in different seasons. Inflow rate is indicated the left axis and shown in grey while total inflow passing through the separator is indicated on the right axis and shown in black.

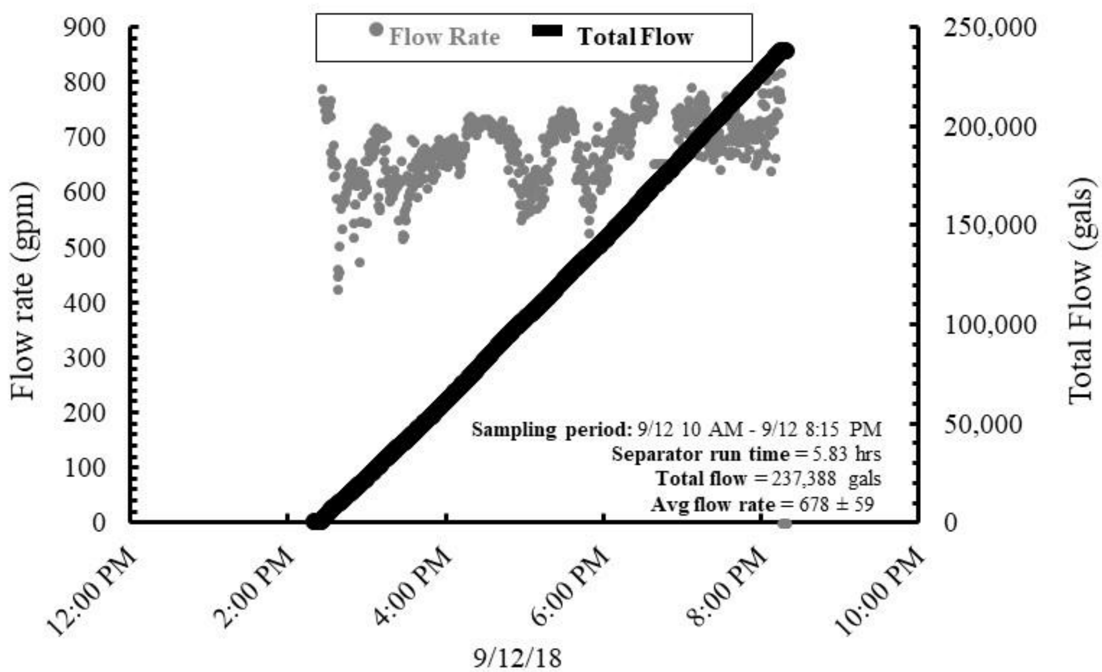

Figure 61. Dairy F: Manure inflow rate and total inflow for the summer season

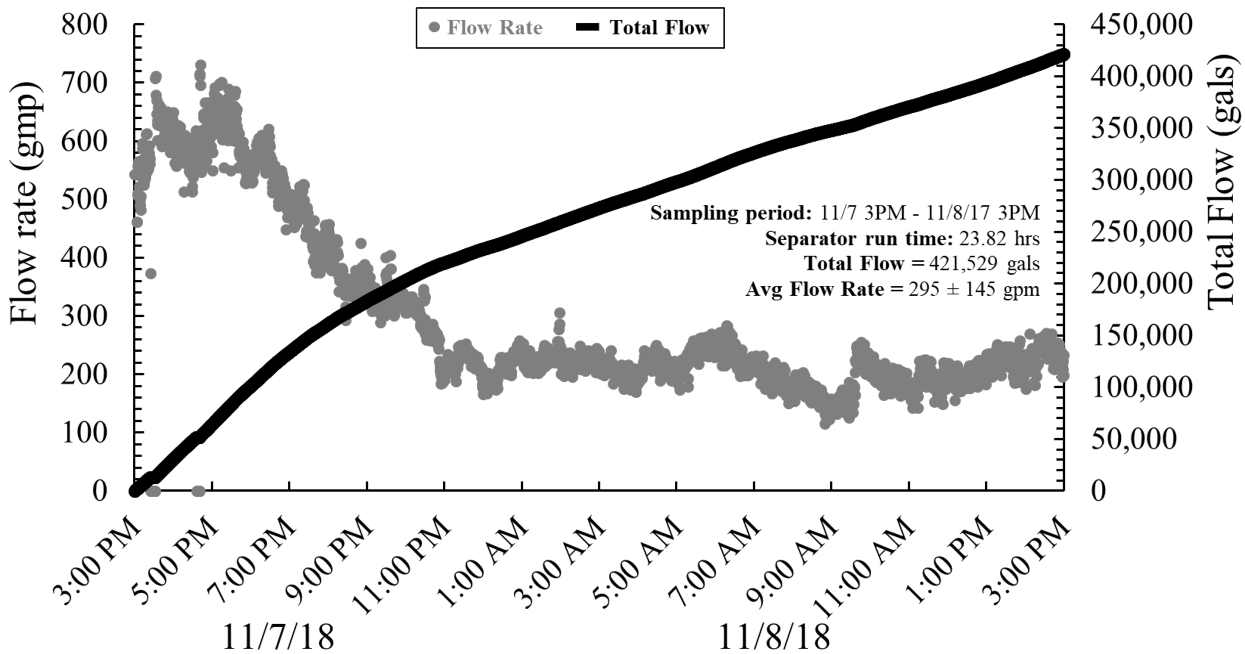

Figure 62. Dairy F: Manure inflow rate and total inflow for the fall season

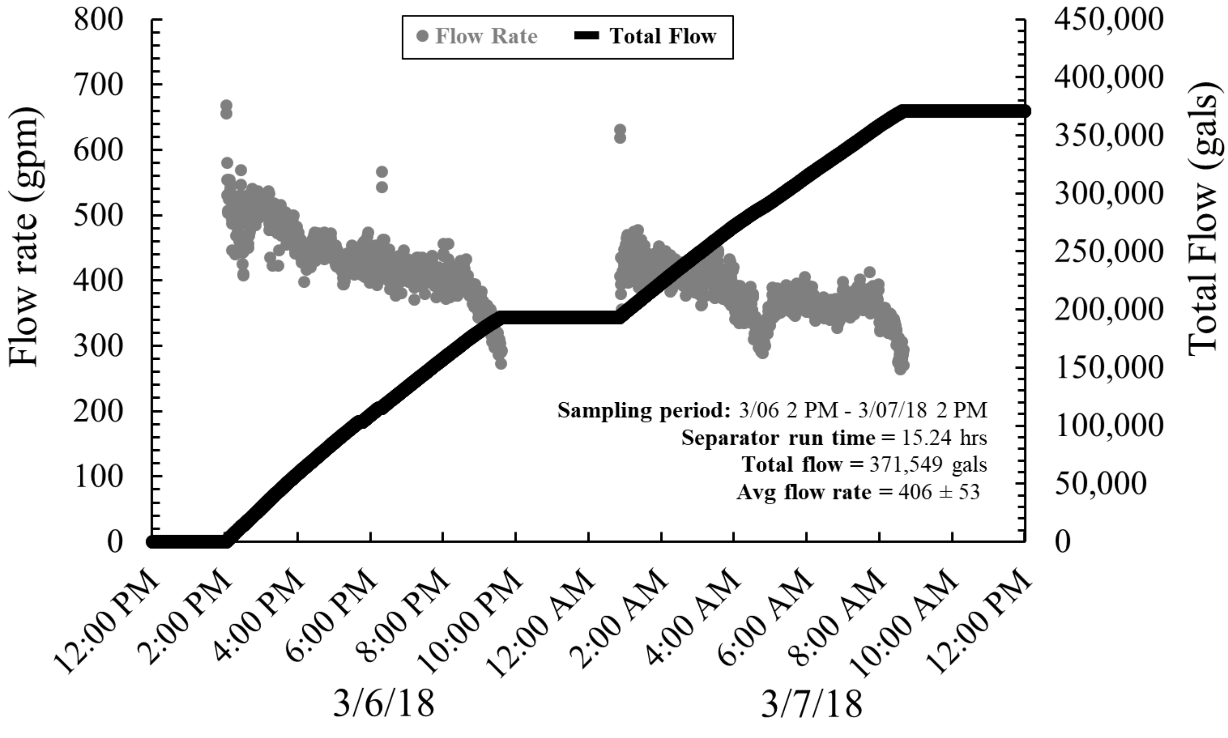

Figure 63. Dairy F: Manure inflow rate and total inflow for the winter season

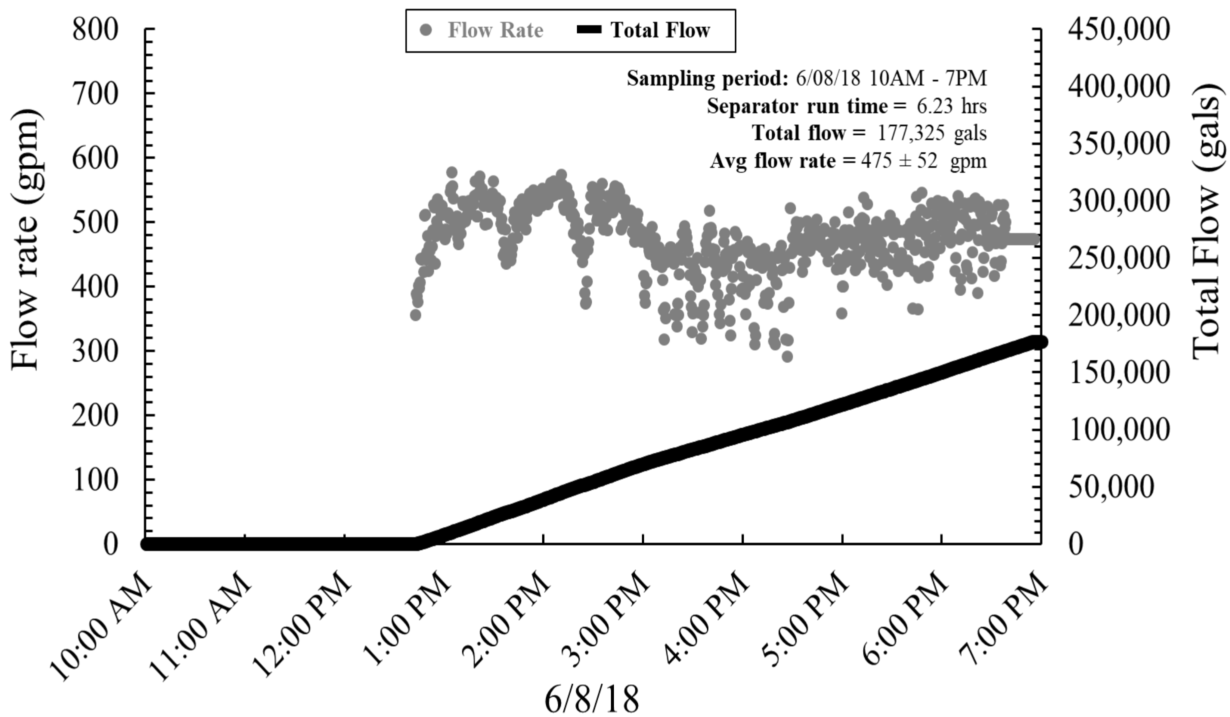

Figure 64. Dairy F: Manure inflow rate and total inflow for the spring season

Table 46 summarizes separator operation during different seasons at Dairy F. The separator pump had ongoing issues on this site throughout the year. During the summer season, the inflow rate was relatively constant during the sampling time and the average inflow rate was 678 gpm. During the fall season sampling, the separator output was initially about 700 gpm in the first hour and then rapidly dropped. The final average inflow rate during the nearly 24 hours of separator operation was 295 ± 145 gpm. The separator pump inflow rate was more consistent in the winter and spring; however, the pump was ultimately rebuilt after the spring season and operated at a much faster inflow rate in the summer sampling. For comparison, the separator operating time in the spring sampling event was 16.61 hours per 24 hours compared to 23.82 and 15.24 hours in the fall and winter, respectively. The total inflow in the spring was 472,855 gallons extrapolating to a 24-hour period compared to 421,529 and 371,549 gallons in the fall and winter seasons.

Table 46. Dairy F: Separator inflow data in different seasons

Parameter	**Units**	**Summer** Sept 2018	**Fall** Nov 2017	**Winter** March 2018	**Spring** June 2018
Sampling period	hrs	9	24	24	9
Operating time	hrs	5.83	23.82	15.24	6.23
Total inflow	gals	237,388	421,529	371,549	177,325
Inflow rate, average	gpm	678 ± 59	295 ± 145	406 ± 53	475 ± 52
Solids	lbs, wb	40,220	127,060	48,920	15,620

Total and Volatile Solids, and pH

Table 47 shows total solids and volatile solids concentration, and pH of separator inlet, outlet, and solids in different seasons, respectively. The separator inlet pH is consistently the lowest followed by the outlet, solids. The inlet of the separator had the highest TS and VS during the fall season. While the lowest values were determined in the spring season.

Table 47. Dairy F: Total and volatile solids concentration (%), and pH of separator inlet, outlet, and solids in different seasons

Sample	Parameter	**Summer** Sept 2018	**Fall** Nov 2017	**Winter** March 2018	**Spring** June 2018
Inlet	TS	1.65 ± 0.40	2.38 ± 0.69	1.81 ± 0.27	1.19 ± 0.17
	VS	1.15 ± 0.33	1.67 ± 0.53	1.30 ± 0.23	0.80 ± 0.14
	pH	7.3	7.2	7.5	7.4
Outlet	TS	1.17 ± 0.19	1.29 ± 0.22	1.44 ± 0.12	0.89 ± 0.05
	VS	0.71 ± 0.13	0.89 ± 0.12	0.92 ± 0.08	0.52 ± 0.02
	pH	7.4	7.3	7.5	7.5
Solids	TS	25.64 ± 0.50	24.28 ± 0.21	23.06 ± 0.92	24.69 ± 0.29
	VS	23.26 ± 0.54	21.50 ± 0.16	21.66 ± 0.90	22.41 ± 0.31
	pH	n.d.[1]	8.1	7.8	7.8

1: Not determined

Biomethane potential testing

Table 48 shows the biomethane potential after 21 days of digestion. The highest biomethane potential of the inlet and outlet were determined during the summer season. The biomethane potential of the separator solids was consistently lower than the inlet and outlet. The BMP of the inlet is lower than the outlet in the summer and fall seasons, and higher than the outlet in the winter and spring seasons. Figure 65 shows methane production potential for Dairy F separator inlet, outlet, and solids in different seasons.

Table 48. Dairy F: Biomethane potential (mL/g[VS]) of separator inlet, outlet, and solids in different seasons

Sample	**Summer** Sept 2018	**Fall** Nov 2017	**Winter** March 2018	**Spring** June 2018
Inlet	221.95 ± 22.4[1]	166.3 ± 3.1	206.9 ± 1.2	192.6 ± 4.7
Outlet	234.15 ± 22.9	187.7 ± 11.7	199.7 ± 6.3	172.1 ± 1.5
Solids	99.05 ± 11.7	87.1 ± 17.1	124.7 ± 6.2	106.5 ± 2.8

1: Average values ± standard deviation between two duplicate reactors

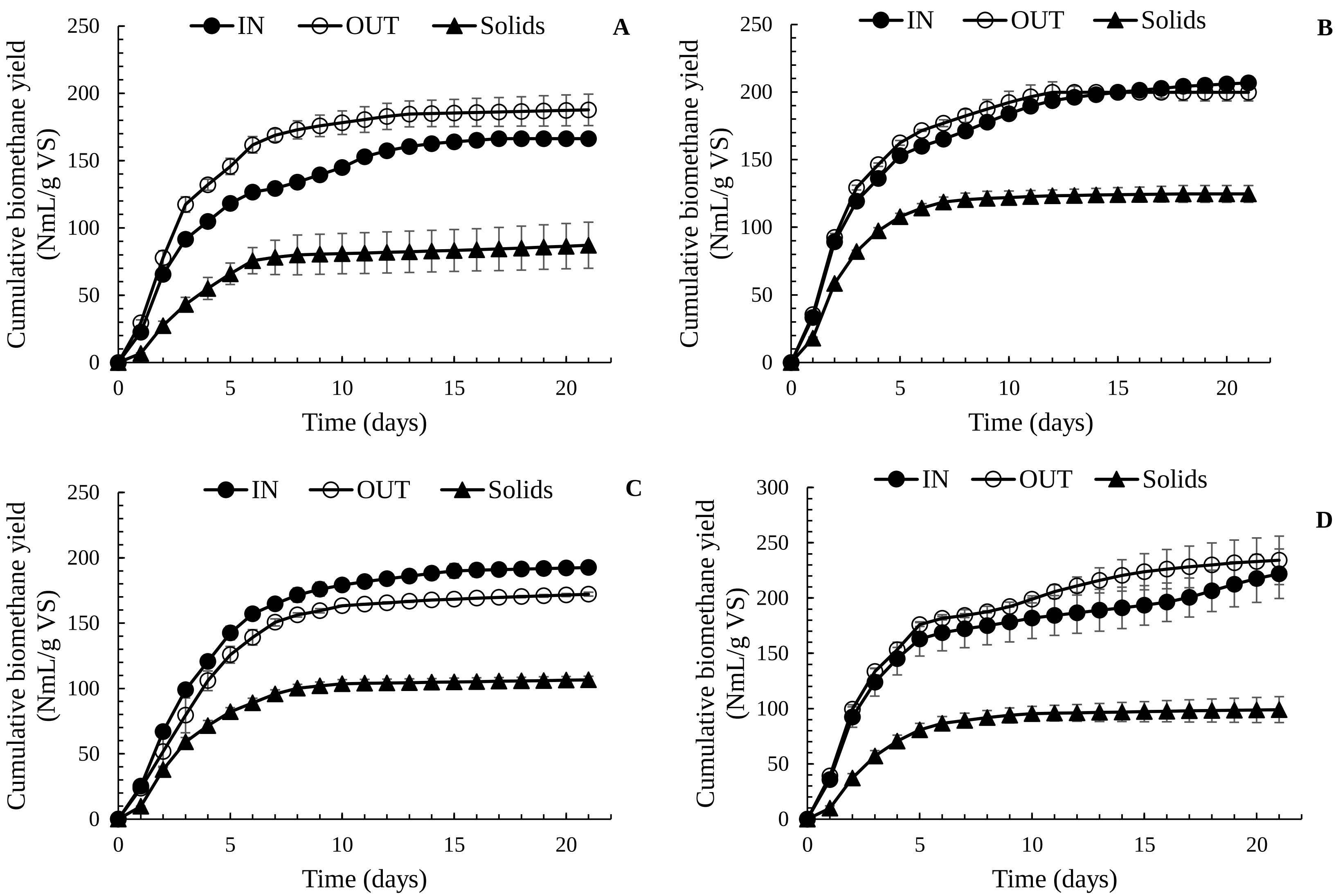

Figure 65. Dairy F: Cumulative biomethane yield in different seasons. **A:** Fall; **B:** Winter; **C:** Spring; D: Summer. Y error bars are standard deviations

Particle size distribution analysis

Figure 66 shows the particle size distribution of composite flushed manure on Dairy F in the Spring sampling event. The particle sizes of ≥ 1mm, < 1mm and ≥ 500μm; < 500 μm and ≥250μm; and < 250 μm and ≥ 75μm represented 19.1%, 8.7%, 8.2%, and 8.4% of the TS, respectively. Approximately 55.7% of the TS were < 75μm and passed the finest screen in the particle size distribution analysis.

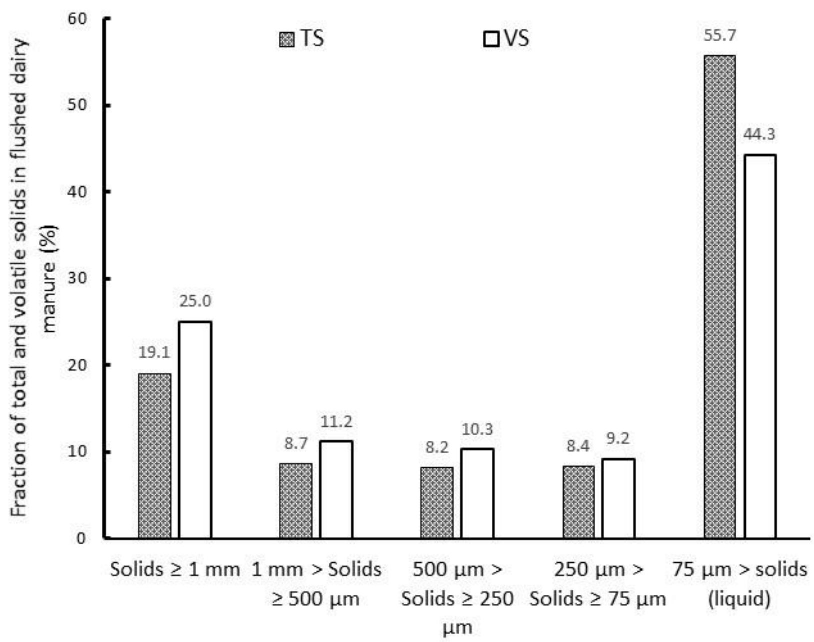

Figure 66. Particle size distribution of the flushed manure on Dairy F

Nutrient analysis

The nutrient concentration in liquid and solid streams for Dairy F are shown in the appendices Tables B 11 and B 12. The removal efficiency of selected nutrients for the three studied seasons are shown in Table 49. As can be seen the average removal efficiency of N, P, K, Na, and Mg were 8.61%, 11.15%, 2.49%, 2.07%, and 8.86%, respectively. The highest removal efficiencies of the selected nutrients were achieved during the fall season. Like other dairies, the lowest efficiencies for removal were Na, and K.

Table 49. Removal efficiencies (%, of the separator inlet) of selected nutrients for Dairy F.

Element	Fall	Winter	Spring	Average
Nitrogen	15.85	6.40	3.58	8.61
Phosphorus	21.15	9.13	3.17	11.15
Potassium	4.34	1.69	1.45	2.49
Sodium	3.63	1.41	1.17	2.07
Magnesium	15.33	5.80	5.46	8.86

Dairy F separator solids removal efficiency and methane potential reduction

Table 50 shows separator performance data for Dairy F's separator in different seasons. The average removal efficiency of TS and VS, and the CH_4 potential reduction were 28%, 36.5%, and 36.55%, respectively. The regression analysis showed a weak negative correlation (R^2 = 0.019) between the separator efficiency and inflow rate. While there was a strong positive correlation (R^2 = 0.523) between the separator efficiency and inlet TS: increasing the inlet TS would increase the separator efficiency. It was mentioned earlier that when separator outlet and inlet biomethane potentials are the same, methane potential reduction from the lagoon equals volatile solids removal efficiency. This can be determined from the data in Table 48, the average biomethane potential over the four seasons of the inlet and outlet were 196.94, and 198.41 ml/g VS. The highest TS and VS removal efficiency, and the CH_4 potential reduction were determined in the fall season while the lowest values were determined in the winter. They are closest in the winter season, resulting in a methane potential nearly the same as VS removal efficiency.

Table 50. Dairy F: Separator total and volatile solids removal efficiencies (%) and methane potential reduction (%) in different seasons

Parameter	**Summer** Sept 2018	**Fall** Nov 2017	**Winter** Mar 2018	**Spring** June 2018	**Average**
TS removal efficiency	31.7	38.4	20.1	21.8	28.0
VS removal efficiency	41.3	48.8	26.4	29.5	36.5
CH_4 potential reduction	38.1	42.2	28.9	37.0	36.6

Economic analysis of the studied separators

Table 51 shows the dairy information, the normalized present worth and the annual-equivalent costs for each separation technology. The annualized cost per cow, including annualized capital investment and operating and maintenance costs, in current dollars range from $26.33 (Dairy F; single-stage sloped screen separator) to $73.41 (Dairy C; advanced separator system) per head per year. Dairy F has the lowest cost mostly because of the existing earthen processing pit, which did not require as much capital cost as the rest of the other dairies. However, concrete processing pits are concluded to be essential for providing a homogenous manure to feed the separator. Dairy C is the most expensive system among the 6 mechanical separator systems. The dairy owner also mentioned that retrofitting the existing site added around 35% of additional costs to the separator system. The advanced separator system also has other benefits, such as the minimum water addition, highly automated processes and better odor control. The dual sloped screen separators (Dairy A and B) require moderate capital and O&M costs based on the analysis. The second stage separator added an additional $21 per head milking cow in the present worth analysis or $2.45 per head milking cow per year in the annual equivalent analysis. The second stage separator could produce finer solids as value added products, such as fertilizers or soil amendment. However, a second separator would require more land space as well as daily maintenance. The horizontal screen separator also has a moderate cost demand among the 6 types of solid liquid separation systems. This specific dairy has a small reception pit, which might be the reason for the overflow of the separator, reducing the overall separation efficiency of the system. This could be solved by remodeling the processing pit but would increase the capital cost of the whole system. The capital cost of the weeping wall system was estimated from a smaller scale weeping wall project from the literature due to the lack of available cost information from the dairy. An 80% scaling up factor in the capital cost was assumed in the economic model. The same method used for the other dairies was applied to estimate the annual O&M cost in the weeping wall system by recording the run time and the pump power acquired on the dairy. The O&M cost per milking cow for the weeping wall was much lower ($2.37/head year) than the other systems (over $11/head year). The lower operating and maintenance cost might be due to the less moving parts in the system. This also means the weeping wall system would be more cost effective for operating a longer period of time. Over a 15-year lifetime, the cost of methane emission reduction ranged from $2.04 to $53.70 per metric ton CO_2 equivalent. The advanced separator system (Dairy C) has the best economic performance in terms of GHG emissions reduction, while the horizontal scraped screen separator (Dairy D) requires the most amount of money for the same amount of GHG emissions reduction. The low separation efficiencies calculated from the previous section might be the reason for the extreme high cost of methane emission reduction at Farm D. It is worth noting that the weeping wall system has a moderate cost of methane emssion reduction with a 15 years' lifespan assumption, which is conservative. The same lifetime of each system is applied here for simple comparison. The economic performance of the weeping wall system could be further improved as the lifetime of the system could be longer than the other mechanical separator systems.

A more detailed economic analysis is needed. That analysis should include; the monetary value of water used in the flushing system, the land needed for installing the separator, diesel consumption for solid handling, the monetary value of the produced solids before and after processing (sun drying and composting).

Table 51. Dairy information and the total present worth and annual equivalent costs for different types of mechanical separators (in current dollars)

Dairy ID	A	B	C	D	E	F
Separator type	Single stage dual sloped screen separator	Two stage dual sloped screen separator	Advanced separator system	Horizontal scraped screen separator	Weeping wall	Single stage sloped screen separator
Years of operation (years)	13	11	4	5	5	5
Dairy size (heads)	2000	3000	2600	750	8000	1850
Daily processing time (hours/day)	6	9	14 (first stage) 21 (second stage)	5.6	6	16
Total cost per cow* ($/head)	363.17	384.19	628.39	343.87	256.72	225.38
Annualized cost per cow ($/head year)	42.43	44.88	73.41	40.17	29.99	26.33
Solid separation cost ($/dry ton)	22.20	14.84	26.46	43.95	13.46	14.73
Annualized cost per CH_4 emission reduction ($/Mt$CO_2$eq)	7.08	5.23	2.04	53.70	4.66	4.79

* Total cost includes capital investment and operating and maintenance costs.

Summary and Conclusions

This study was the first of its kind to comprehensively evaluate the performance of multiple operational solid separation technologies with regards to solids and nutrient removal efficiencies and methane reduction potential from flushed manure on California dairies. In order to perform this study, the research team developed a mass balance methodology to quantify the performance of various mechanical separators and weeping wall. Although this method is more time and labor intensive than other methods, it allows more accurate determination of the amount and characteristics of solid and liquid streams from the separator systems and methane reduction potential.

The field work of this project began in July 2017 and was concluded in December 2018. Six dairies and five different types of solid-liquid separators were studied. Five Dairies employed mechanical solid-liquid separators (Dairies A, B, C, D, and F) while one had a weeping wall (Dairy E). Dairies A and B had 1 and 2 stage sloped dual-screen separators, respectively, both of which were from the same manufacturer. Dairy D had a 1-stage horizontal scraped screen system. Dairy F had a 1-stage sloped single-screen separator from a manufacturer different from Dairies A and B. Dairy C was chosen for its unique and advanced multistage separator system that incorporates 2 stages of rotary drum separators with settling tank between the two stages. Finally, Dairy E had a weeping wall system. Mechanical separators were sampled and measured up to four times, once each season, when possible. Dairies A, C, and F were sampled four times. Dairies B and D were sampled three times. Due to its complexity and additional time required to study the weeping wall system, Dairy E was sampled twice.

All six dairies employed flush manure management systems. Freestall lanes were flushed by a combination of one or more of the following liquid streams on the dairy: lagoon water, fresh water, milk parlor process water, and/or recycled flush water from a manure collection pit. Flush manure flowed from the barns to a manure collection pit of various sizes and construction. Some were small, earthen reception pits that simply stored and transferred the flush manure to the separator. Others were more advanced, large, concrete processing pits providing the system with buffer capacity and homogenization of flush manure prior to separation. Sand lanes were also installed before the processing pit to remove sands before pumping the flushed manure to the separators. Screened flush manure travelled to one of the following: a settling basin, a lagoon, to a second, finer screen separator for further solids removal, or in the case of Dairy C to a settling tank. While some dairies employed settling basins (Dairies B, C, D, F), others (Dairies A, E) did not. In all the cases, separated solids were dried and conditioned for reuse as bedding and/or soil amendment that could also include other materials such as excavated lagoon and settling basin solids, sand, corral solids, and/or almond or other type of nut shells. Separator performance was determined with respect to solids removal efficiencies and methane potential reduction. This was accomplished by conducting dairy sampling work, consisting of sampling the separator inlet and outlet, measuring the flow of flush manure into the separator, and sampling and weighing the solids removed by the separator in a given sampling period. Samples were collected at regular intervals and taken back to the Bioenvironmental Engineering (BEE) Research Laboratory at UC Davis where they were composited and analyzed for total and volatile solids, pH, biomethane potential, particle size distribution, and nutrient contents. The data of flow, total and volatile solids, and biomethane potential were used to determine total and volatile solids removal efficiencies and methane potential reduction.

The performance of the mechanical screen separators depended on manure characteristics, system design (e.g., screen size and orientation), separator operation and management (manure flow rate), and manure processing pit type and configuration. For example, the low efficiency of TS and VS removal and methane potential reduction on the D dairy might be attributed to the largest screen size (2,380 µm) and different shape (round holes) as compared with other screen separators. Moreover, the system was not well managed, and it was undersized as we have noted that large quantities of flushed manure were overflowing over the separator without going through the screen. The advanced separation system achieved the highest removal efficiency of TS and VS, and methane potential reduction. This might be due to the emissions from the settling tank though the retention time in the settling tank is short. More research is needed to quantify the emissions and solids degradation within the system. Moreover, the high removal efficiency of the TS and VS from the weeping wall system and consequently the high methane potential reduction could be attributed to the aerobic and anaerobic degradation of the organic matter in the weeping wall cells during the filling and storage periods of the cells. More research is also needed to quantify the emissions from the weeping wall during the filling and storage (draining) times.

The regression analysis of the data collected for the Dairies A, B, C, D, and F showed a correlation between separator efficiency and either inflow rate or the inlet TS. A more detailed study is needed to increase the frequency of measuring the separators efficiency (e.g., monthly) over the year to conduct multiple regression analysis to correlate the separator efficiency and both the inflow rate and inlet TS.

The biomethane production potential (BMP) of the composite samples showed a pronounced variation between different streams (inlet, outlet, and solids) and different dairies. The variations could be attributed to several factors including: (1) screen sizes that affect the amount of solids retained over the screen and that passed through the screen openings; (2) the quality and quantity of the water used in manure flushing: reuse of lagoon water could reduce the BMP due to the recycling of the recalcitrant VS; (3) the quantity and quality of bedding materials: reusing of bedding materials could reduce the BMP due to the loss of easily biodegradable materials during the bedding preparation (sun drying or compost) and recycling; (4) the chemical composition of manure and flushing water (i.e., lagoon and milking parlor): proteins and fats have higher BMP than carbohydrates. For most of the studied dairies, the solids stream had the lowest BMP, which may be attributed to the fact that the separated solids are fibrous and composed mainly of lignocellulosic materials (i.e., carbohydrates). Table 52 shows a summary of the specifications and the performance of the studied systems.

Table 52. A summary of the specifications and the performance of the studied systems.

Parameter		Single-stage horizontal scraped screen separator	Single-stage sloped single-screen separator	Single-stage sloped dual-screen separator	Two-stage sloped dual-screen separator	Advanced multistage separator system	Weeping wall*
Screen size (inch)	1st stage	0.094	Top 1/3: 0.015 Middle 1/3: 0.025 Bottom 1/3: 0.035	Top 2/3: 0.020 Bottom 1/3: 0.025	Top 2/3: 0.020 Bottom 1/3: 0.025	Separation zone: 0.125 Dewatering zone: 0.125	An inch to several inches
	2nd stage	NA	NA	NA	Top 2/3: 0.010 Bottom 1/3: 0.015	Separation zone: 0.021 Dewatering zone: 0.125	NA
Capital investment ($)		130,553	125,113	531,289	656,167	1,052,142	1,891,251
O&M cost ($/year)		14,878	34,095	22,788	57,993	67,957	18,989
Annualized cost ($/head year)		40.17	26.33	42.43	44.88	73.41	29.99
Cost of CH_4 emission reduction ($/MtCO2eq)		53.70	4.79	7.08	5.23	2.04	4.66
Influent flow rate (gpm)		790-1507	295-678	841-1089	696-932	938-1516	802-980
TS removal efficiency (%)		4.7-8.0	20.1-38.4	27.7-48.9	37.6-60.2	64.2-78.8	78.4-81.9
VS removal efficiency (%)		6.5-12.1	26.4-48.8	35.5-58.4	41.4-72.8	62.7-79.6	79.0-86.1
CH_4 potential reduction (%)		1.4-8.4	28.9-42.2	38.2-57.2	28.2-73.1	69.0-83.4	75.4-80.6
Nitrogen removal (%)		0.12-0.55	3.58-15.85	9.11-30.09	10.84-32.74	3.25-9.46	18.62-27.59

*This system was evaluated for two cells

Dairy A's separator was sampled on four days, once each season. During the four seasons, separator inlet TS and VS varied on average 1.57% to 2.59% (wet basis) and 1.12% to 1.85% (wet basis), respectively. Separator inlet, outlet, and solids biomethane potential were on average 204.7 ± 46.5, 213.8 ± 43.0, and 140.0 ± 35.0 mL/gVS, respectively. Over the four seasons, TS removal efficiency, VS removal efficiency, and methane potential reduction were on average 41.0%, 52.1%, and 50.0%, respectively.

Dairy B's separator system was sampled in the summer, winter and spring seasons. During the three seasons, separator system inlet TS and VS varied on average 2.53% to 3.73% and 1.96% to 2.76%, respectively. Separator system inlet, midpoint, outlet, coarse and fine solids biomethane potential were on average 199.8 ± 17.7, 217.4 ± 25.4, 211.5 ± 30.7, 161.2 ± 37.0, and 147.3 ± 29.5 mL/gVS, respectively. Separator performance data has only been determined for 3 seasons. The average TS removal efficiencies for 1st stage, 2nd stage, and the full system were 48.3%, 4.3%, and 52.5%, respectively. The average VS removal efficiency for the first stage, second stage, and full system were 55.9%, 3.8%, and 59.7%, respectively. Methane potential reduction for the 1st stage, 2nd stage, and full system were 49.9%, 5.9%, and 55.8%, respectively.

The results of the dairy A using a single stage dual sloped screen separator and the dairy B that employed two stage dual sloped screen separations system are in agreement with those obtained by Chastain (2009) who evaluated the performance of a two-stage mechanical separation system that was installed on a Dairy Farm in Tulare, California. The system consisted of two inclined screens operated in series. The first and second screen had openings size of 0.020 and 0.010 inches, respectively. The first stage of the system is similar to the system employed on the dairy A; and the system is similar to that employed in the dairy B. Chastain employed a comparable evaluation method to what was used in this study. He calculated the efficiency of solids removal of each stage based on the weight of solid separated and the weight of solids in the influent of each stage. The removal efficiency of the total solids for the first stage, second stage, and the whole system (both stages) was 50.3%, 9.4%, and 59.7%, respectively. The removal efficiency of volatile solids was 56%, 9.7%, and 65.7%, respectively.

Dairy C's separator system was sampled in four seasons. The first stage separator inlet TS and VS varied on average 1.49% to 1.88% and 0.92% to 1.36%, respectively. The first stage separator outlet TS and VS varied on average 1.42% to 1.79% and 0.82% to 1.27%, respectively. The second stage separator inlet TS and VS varied on average 3.54% to 4.20% and 2.28% to 3.01%, respectively. Separator first stage inlet and outlet, second stage inlet and outlet, and coarse and fine solids biomethane potential were on average 263.2 ± 17.9, 248.9 ± 36.4, 203.8 ± 17.5, 227.0 ± 25.8, 150.7 ± 25.0, and 167.9 ± 18.9, respectively, across all 4 seasons. TS removal efficiency for first, second stage, and full system were on average 7.9%, 12.1%, and 69.4%, respectively, for summer, winter and spring seasons. VS removal efficiencies for first and second stage, and full system were on average 10.6%, 14.2%, and 69.7%, respectively, for summer, winter and spring seasons. Methane potential reduction for first, second stage, and the full system were on average 21.0%, 30.0%, and 74.8%, respectively, across for summer and winter seasons. The fall season data was not presented because of the lack of the flow information from settling tank to the second stage separator.

Dairy D's separator was sampled in the four seasons. The original Dairy D site was sampled in the fall season; however, this dairy was eventually replaced due to complications with measurements on the site and data has not been analyzed. During the other three seasons, separator inlet TS and VS concentrations varied on average 1.47% to 1.72% and 0.90% to 1.14%, respectively. Separator outlet TS and VS concentrations varied on average 1.12% to 1.60% and 0.60% to 1.04%, respectively. Separator inlet, outlet, and solids biomethane potential were on average 147.5 ± 10.2, 156.9 ± 6.1, and 125.4 ± 3.9 mL/g VS, respectively, during the summer, winter and spring seasons. The average TS and VS removal efficiencies for Dairy D's separator were 6.3% and 9.3%, respectively, across the three seasons. The average methane potential reduction for Dairy D's separator were 4.9%, during the summer and spring seasons.

Two cells of weeping wall on Dairy E were evaluated during the fall and early winter seasons. The average inlet TS and VS of the two cells were 1.71%, and 1.25%, respectively. The average outlet has TS and VS contents of 1.07% and 0.77%, respectively, while the TS and VS of the solids removed from the two cells were 24.12% and 18.15%, respectively. The biomethane potential for the inlet, outlet, and solids were 230.75, 294.38 and 74.14 mL/g[VS], respectively. The average TS removal efficiency, VS removal efficiency, and methane potential reduction for were 80.2%, 82.6% and 78.0%, respectively. The average determined removal efficiency of TS lies in the range stated in the literature and weeping walls designers. Meyer et al. (2004) evaluated the effectiveness of weeping wall on a 1100-cow commercial dairy in California by sampling manure for four sampling events: three events in March and one in July. The influent mean TS concentrations was 1.52%. Fixed solids ranged from 37.02% to 45.92% of the TS. The weeping wall removed manure particles that are greater than 0.125 mm. The average TS removals were in the range of 49.3% to 63.4%. No sampling was conducted for the solids retained in the weeping wall. Nooyen (2018) mentioned that the Tri-Bar weep walls system could effectively remove 60% to 85% of total solids and up to 70% of sand. NRCS (2014) reported a solid removal efficiency of the weeping walls in the range of 50% to 85%.

Dairy F's separator was sampled in four seasons. During the four seasons, separator inlet TS and VS concentrations varied on average 1.19% to 2.38% and 0.80% to 1.67%, respectively. Separator outlet TS and VS concentrations varied on average 0.89% to 1.44% and 0.52% to 0.92%, respectively. Separator solids TS and VS concentrations varied on average 23.06% to 24.69% and 21.50% to 22.41%, respectively. Separator inlet, outlet, and solids pH were on average 7.35, 7.42, and 7.9, respectively. Separator inlet, outlet, and solids biomethane potential were on average 196.94 ± 23.68, 198.41 ± 26.37, and 104.34 ± 15.75 mL/gVS, respectively. TS removal efficiency, VS removal efficiency, and methane potential reduction were on average 28.0%, 36.5%, and 36.6%, respectively.

The economic analysis showed that that the lowest and highest annualized cost per milking cow was for the single sloped screen separator, and the advanced separator system, respectively. However, the advanced separator system had the lowest cost of methane emission reduction (\$2.04/MtCO_2eq) due to its highest methane reduction potential. The annualized cost per cow for all the studied mechanical screen separators was in the range of \$26.33 to \$73.41 per cow per year. The weeping wall seems to be the most economic system; as it achieved a high reduction in methane production potential while the annualized cost was approximately \$30 per cow. Although the weeping wall was simple to operate and had minimal maintenance costs and down time, the system requires more space than other mechanical separators. Also, the emissions from the solids accumulated in the weeping wall cells during the filling and drying need to be determined in future research. A more detailed economic analysis including the labor costs and the price and potential use of the separated solids is needed to evaluate the most economic manure separation system. Moreover, it would be also recommended to conduct a life cycle analysis of the studied manure management systems to determine the effect of separated solids and the energy used in their management on the emissions from the dairies.

Lessons learned and future research needs

The mass balance approach applied in this study for evaluating different separate technologies is appropriate for future studies to evaluate manure separation technologies. In addition to its usefulness in quantifying methane emission reduction potentials, it can also be used for determining the amount of solids diverted from the lagoons. The separated solids could be used for animal bedding, compost and other applications. Additional research could be completed to compare the mass balance approach used in this study to other simpler methodologies in order to determine if there are situations where less intensive measures could provide sufficient accuracies.

The data obtained in this study showed significant variation in the efficiencies of solid separation and methane reduction potential across technologies and different seasons. More data are needed in order to capture the variability of flushed manure characteristics and separator performance as well as greater understanding of the effects of dairy feeding and management practices (e.g. feed type, water and bedding recycling, flush schedule) on the performance of separators is needed. Such data would allow better understanding of how and why the system efficiencies and methane reduction potentials change over the course of a year. With more frequent measurements of the separator efficiency, it will also be possible to develop multiple regression equations to determine the separator efficiency as a function of manure inflow rate and inlet TS. This will aid in the proper sizing and design of separators in the future.

Moreover, more research is also needed to determine the effect of flush water quality on the separator efficiency. Sampling and characterization of flush valves contents before entering the barns would provide insight into the origin of the separated manure solids. This is important as it would allow for a determination of separator efficiency that includes manure solids while excluding solids recycled from the lagoon.

There was significant variation in the pre-separation processes (such as sand traps and processing pits) employed by the different dairies in this study. Employing an earthen processing pit as opposed to a concrete processing pit, while cheaper upfront, may cause complications to separator-associated equipment in the long term due to increases in the amount of sand delivered to the separator. This may increase the wear of pumps and other moving parts in the system. Moreover, well designed processing pits with homogenous mixing may help to assure consistent separator efficiencies are achieved by the system. Despite the obvious importance of these preprocessing unit operations, very little data are available on their effect on separator performance.

The management of the solids separated varied among the studied dairies. While some dairies use sun drying to produce bedding materials, others use composting to produce soil amendments or bedding. The emissions from different solids management practices should be determined. Moreover, the energy and labor needed to manage these solids should be determined in future studies. More research is needed to study the fate of the VS in the settling tanks of the Dairy C.

It was noticed that applying higher inflow rates than the designed values caused overflow where a considerable amount of the inflow was delivered to the manure storage lagoon without separation. Therefore, separator sizes should be selected to both match the expected manure inflow rates and accommodate any potential increases in herd size. On-farm flow rate measurements are essential for proper separator sizing. Safety factors should be included in separator sizing calculations to accommodate unexpected flow rates and ensure that all manure passes through the separator without interruption of normal dairy operation activities.

The weeping wall system occupies a larger land area than other studied systems. This should be considered in future research to evaluate the economics of the separator systems. The filling time of the weeping wall may vary slightly for different cells depending on the TS contents in the influent, the manure flow rate, and the availability of equipment and labor. It should be mentioned that there may be emissions of PM2.5 and NOx from the loader employed to empty the cells and the trucks used for transportation of the solids to the compost facility that is located at about 0.5 miles from the weeping cells. These emissions should be determined in future research. It was also noticed that there was spatial variation in the TS and VS contents of the solids accumulated in the weeping wall. More research is needed to determine the source and extent of such variations and to evaluate the processes involved in the degradation of the organic matter during the filling, drying, and emptying of weeping wall cells.

More research is also needed in the following areas:

- The relationship between methane mitigation and separation efficiency (lab- or field-based) must be determined in long-term experiments for different mechanical separator systems. This would entail increased measurement frequency within and across seasons. The effects of feed changes, bedding recycling, and climatic conditions on the methane reduction potential of the separator systems would thus be possible to determine. This information would add necessary information about the factors that influence solid-liquid separation performance and would allow for greater accuracy in methane emission prediction models.
- The effects of pre-separator manure processes (such as sand traps and processing pits) on the performance of solid-liquid separation systems must be investigated. This would provide insight into the processes that are necessary to be used prior to different solid-liquid separation systems for optimal performance.
- Quantify and characterize seasonal variations in flush water composition with and without lagoon water recycling. This information could be used to inform a new, potentially more accurate separator efficiency model.
- The solids used for animal bedding need to be characterized for their amount, nutrient contents, and particle size distribution and their impact on the separator performance should be investigated.
- Costs and benefits of various types of separators and their processing systems need to be further analyzed in order to determine the most economical systems for dairies to implement, with

considerations of nutrient management, value-added manure products and mitigation of methane and other air emissions.
- The standard methodology for sample collection, inflow measurement, separation efficiency, and methane emission reduction from manure systems need to be developed.
- The correlation between lab-based biomethane reduction potential results and the actual measured methane emission reduction from lagoons as a result of employing solid separation systems needs to be developed.

Project Impacts

The major contributions, accomplishments, innovations, and successes that have come about as a result of this project include:

- Was most comprehensive study evaluating solid-liquid separator performance at the dairy farm scale and under real operating conditions.
- Highlighted the importance of solid separators in reducing GHGs on the dairies.
- Demonstrated significant differences and variability of performances of different separators and impact of governing factors (e.g., screen size, inflow rate, and inlet total solids).
- Developed more accurate on-farm sampling and laboratory testing methodology for evaluating the performance of separators.
- Obtained extensive datasets for flushed manure characteristics and methane potential before and after separators across different seasons.
- The results of this study point out the need for revising the separator efficiency values used in the GHG calculator by the California Air Resources Board for Alternative Manure Management Practices.
- The data will be useful for developing new models for predicting methane emissions from anaerobic lagoons.

The results of this study will help show dairy producers the utility of solid-liquid separators as effective manure management technologies, and will impact dairy producers and the dairy industry in the following ways:

- Encouraging wider adoption of separators on dairies, and
- Informing dairy operators about various solid separation technologies in order to select proper separator that meet their goals.

Outreach Activities Summary

Date: 09/18/2017
Location: Sacramento, CA
Event: Dairy and Livestock Working Group, Subgroup #1 meeting
Oral Presentation Title: "Research in Progress: Effect of Solid Separation on Mitigation of Methane Emission from Dairy Manure Lagoons"
Number of participants: Live audience 25-50 people and online participants unknown
Type of audience: Industry, government, academia, and the public
Website: https://www.arb.ca.gov/cc/dairy/dsg1/dsg1.htm

Date: 11/01-02/2017
Location: The Ziggurat building, Sacramento, CA
Event: California Bioresources Alliance Symposium
Poster Presentation Title: "Effect of Solid Separation on Mitigation of Methane Emission from Dairy Manure Lagoons"
Number of participants: 100+ people
Type of audience: Industry, government, academics, and the public
Event website: https://www.epa.gov/ca/2017-california-bioresources-alliance-symposium

Date: 02/14/2018
Location: Southern California Edison Education Center, Tulare, CA
Event: Annual business meeting: American Society of Biological & Agricultural Engineers California Nevada (ASABE CA/NV) section
Poster Presentation Title: "Effect of Solid Separation on Mitigation of Methane Emission from Dairy Manure Lagoons" won first place graduate poster award
Number of participants: 100 people
Type of audience: Industry, government, and academics
Event flyer:

American Society of Agricultural and Biological Engineers
California-Nevada Section
www.asabecanv.org

ANNUAL MEETING

Date: Wednesday – February 14th, 2018 (during the World Ag Expo)
Time: 5:00 p.m. – 8:30 p.m.
Location: Southern California Edison's Energy Education Center - Tulare
4175 South Laspina (across from the World Ag Expo)
Tulare, California 93274
Ticket Cost: $35 for members/guests, $12 for students

AGENDA

5:00 PM Poster Competition and Reception
6:00 PM Dinner
6:30 PM Business Meeting
7:00 PM Featured Speaker:

Oroville Dam Spillway Repair
Dale Brown (Supervising Engineer, Dept. of Water Resources)

Dale Brown is a Supervising Engineer with the Department of Water Resources. Through-out 2017 he was the Deputy Project Manager for the Oroville Emergency Recovery – Spillways team, overseeing portions of the Engineering section through-out both design and construction. Prior to working on Oroville, he managed both programs and projects during his 11 years with the State and 6 years in the private industry.

8:10 PM Closing Comments
8:15 PM Adjourn

STUDENT POSTER COMPETITION

Poster presentations will be part of the meeting again this year. This has been a great opportunity to see student projects. We will be awarding prizes for first place ($250) and second place ($100) in both the undergraduate and graduate student categories. Winners must be present to receive their award. **Please limit your tri-fold poster size to 36"Hx48"W or flat posters to 34"Hx44"W. Tables will be available. If your poster requires an easel, or backing for stability, please provide it.** Thank you to our student dinner sponsors. If you would like to become a student sponsor, please contact Balaji Seth at (559) 321-6826 or balajis@csufresno.edu

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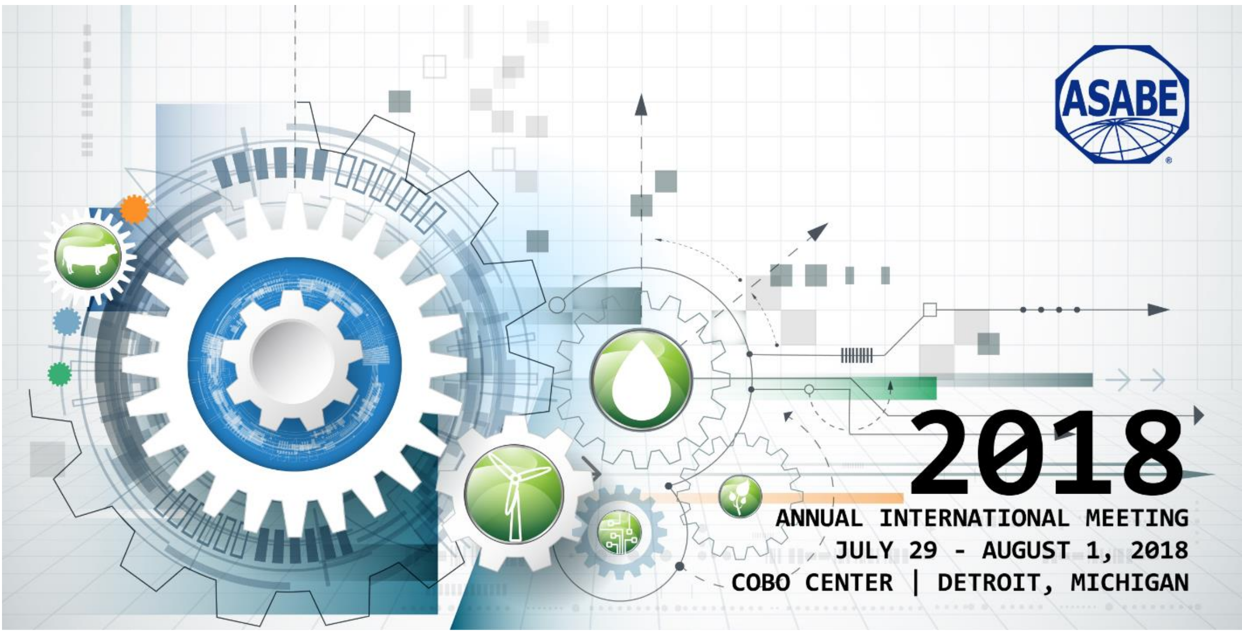
Please RSVP to Traeger Cotten (contact info below) by mail or email no later than February 7th. Payment will be accepted at the door. Please make checks payable to "ASABE CA/NV Section".

Traeger Cotten
2425 South Blackstone Street
Tulare, CA 93274
Mobile: (559) 331-9715
Email: traeger.cotten@sce.com

Dinner: "Mexican Fiesta" includes Beef Enchiladas, Chili Verde, Steak Ranchera, Chicken Oregatino, Green Salad, Refried, Beans, Spanish Rice, Tortillas, Salsa, Dessert, and Beverages.

Date: 04/21/2018
Location: UC Davis Dept Bio & Agricultural Engineering, Bainer Hall, Davis, CA
Event: 104th annual UC Davis Picnic Day
Poster Presentation Title: "Effect of Solid Separation on Mitigation of Methane Emission from Dairy Manure Lagoons"
Number of participants: Several 100 people
Type of audience: Industry, government, academics, and the public
Website: https://picnicday.ucdavis.edu/

Date: 07/29-08/01/2018
Location: Cobe center, Detroit MI
Event: American Society of Biological and Agricultural Engineers (ASABE) Annual International Meeting (AIM)
Oral Presentation Titles: "Effect of Solid Separation on Mitigation of Methane Emission from Dairy Manure Lagoons" and "Particle Size Distribution and Effect of Solid Removal on Biomethane Potential Reduction in Flushed Dairy Manure"
Number of participants: 25-50 people (Conference total 1,740)
Type of audience: Industry, government, academics, and the public
Event advertisement:



Date: 11/14-15/2018
Location: The Ziggurat, Sacramento, CA
Event: California Bioresources Alliance Symposium
Oral Presentation Titles: "Effect of Solid Separation on Mitigation of Methane Emission from Dairy Manure Lagoons"

Number of participants: 100+ people
Type of audience: Industry, government, academics, and the public
Event website: https://www.epa.gov/ca/2018-california-bioresources-alliance-symposium-agenda-speaker-bios-and-presentations

Date: 11/27-28/2018
Location: Sacramento, CA
Event: 1st California Dairy Sustainability Summit
Oral Presentation Titles: "Effect of Solid Separation on Mitigation of Methane Emission from Dairy Manure Lagoons"
Number of participants: 660+ people (including 201 registered dairyproducers)
Type of audience: Industry, government, academics, dairy producers, and the public
Event website: https://www.caDairiesummit.com/

Date: 02/13/2019
Location: Southern California Edison Education Center, Tulare, CA
Event: Annual business meeting: American Society of Biological & Agricultural Engineers California Nevada (ASABE CA/NV) section
Oral Presentation Titles: "Effect of Solid Separation on Mitigation of Methane Emission from Dairy Manure Lagoons" won first place graduate poster award
Number of participants: 100 people
Type of audience: Industry, government, and academics
Event flyer (next page):

American Society of Agricultural and Biological Engineers
California-Nevada Section
www.asabecanv.org

ANNUAL MEETING

Date: Wednesday – February 13th, 2019 (during the World Ag Expo)
Time: 5:00 – 8:30 pm
Location: 4175 South Laspina (across from the World Ag Expo)
Tulare, California 93274
Ticket Cost: $35 for members/guests, $12 for students

AGENDA

5:00 PM **Poster Competition and Reception**
6:00 PM **Dinner**
6:30 PM **Business Meeting**
7:00 PM **Featured Speaker:**

CLAAS Farming 4.0 and a Global Perspective on International Agribusiness
Maury Salz, President, ASABE and CLAAS Omaha, Inc.

Maury Salz grew up on a family farm in Northwest Iowa and still participates in his family's corn and soybean farming operations. He has worked for CLAAS for 18 years and will provide insights into the CLAAS Farming 4.0 way of thinking, about precision farming, big data, and the worldwide relationships that are needed to develop products and processes to support the complex farming operations of the future. Maury will also give an update on how ASABE is working to support 5 major goals which will support Agricultural and Biological Engineers into the future.

8:10 PM **Closing Comments**
8:15 PM **Adjourn**

STUDENT POSTER COMPETITION

The student poster competition will begin promptly at 5PM. Guests will have time to view posters for 30 mins after which, voting will determine the winners. We will be awarding prizes for first place ($250) and second place ($100) in both the undergraduate and graduate student categories. Winners must be present to receive their award. **Please limit your tri-fold poster size to 36"Hx48"W or flat posters to 34"Hx44"W. Tables will be available. If your poster requires an easel, or backing for stability, please provide it.** Thank you to our student dinner sponsors. To become a student dinner sponsor, please contact Hossein Edalati (530-220-2489 or ahedalati@gmail.com).

Please RSVP to Traeger Cotten no later than February 8. Payments will be accepted at the door. Please make checks payable to "ASABE CA/NV Section."

Traeger Cotten
2425 South Blackstone Street
Tulare, CA 93274
Mobile: (559) 331-9715
Email: traeger.cotten@sce.com

Dinner: "Mexican Fiesta" includes beef enchiladas, chili verde, steak ranchero, chicken oregatino, green salad, refried beans, Spanish rice, tortillas, salsa, dessert, and beverages

Date: 07/07-10/2019 (Future event)
Location: Boston Marriott, Boston, MA
Event: American Society of Biological and Agricultural Engineers (ASABE) Annual International Meeting (AIM)
Oral Presentation Titles: "The Impact of Mechanical Solid Separators on the Mitigation of Methane Emissions from Dairy Manure Lagoons," "The Impact of a Unique, Advanced Multistage Solid-Liquid Separator System on the Mitigation of Methane Emissions from a Dairy Manure Lagoon in California," "An Economic Analysis of Solid Separation Technologies on Selected California Dairy Dairies," and "Predicting the Efficiency of Solid Separators on Dairy Dairies Using Particle Size Distribution Measured in the Laboratory"
Poster Presentation Titles: "The Impact of a Weeping Wall on the Mitigation of Methane Emissions from a Dairy Manure Lagoon in California"
Number of participants: TBD
Type of audience: Industry, government, academics, and the public
Event advertisement:

References

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Sousa Family
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Appendices

Appendix A: General Dairy Questionnaire

This past quarter a dairy questionnaire was designed and sent to each dairy owner. The questions cover a general dairy description, manure management, dairying system, solids management and bedding, and specific information to each sampling such as herd size and feed composition. Some of the information requested is very detailed and may not be easily accessible; however, the goal is to compile as much of the information as possible. A copy of the questionnaire is provided below:

Dairy Site Questionnaire

GENERAL

1. **Dairy name and address.**

2. **History of operation.**
   Number of years in operation
   Modifications and changes over the years.

3. **Herd type and milk end use.**

4. **Dairy herd size (milking, dry, heifer).**
   Dairy herd size of milking, dry, and heifers. Comments on year round variability or herd size. Info on which cows have all their manure enter the flush stream versus other areas such as corrals. Also any changes in how the Dairies are managed year round that might affect where the manure ends up.

5. **Animal feed amount/composition & year round feed variability.**
   Feed mix, composition, estimated relative amount consumed per animal per day and comments on how that changes over the course of the year. Year round changes in feed mix, composition, and amount consumed.

6. **Supporting offsite Dairies/sites.**
   Offsite dairy or land supporting this dairy operation.

7. **Dairy land size (total, dairy, dairying acreage).**
   Total: Total land, dairy, dairying, plus any other site acreage
   Dairy: Land dedicated to the dairy operation
   Dairying: Land dedicated to dairying
   Offsite: Offsite supporting land for the dairy

8. **Infrastructure: barns and exercise pens/corrals (type, number, and dimensions)**

MANURE MANAGEMENT SYSTEM

9. **Unit operations.**

10. Dimensions.

Lagoons:
Settling ponds:
Processing pit:
Sand pit:
Separator:

11. Detailed manure management system description in order of unit operation tracking flush water from barns through to the lagoon.

12. Flush frequency, valve map, program description, flush water flowrate out of valves, and flush water source and quantity (lagoon, recycled pit water, milk parlor water, fresh water, etc.).

Milk parlor water – frequency? Quantity?
Fresh water – sprinklers, quantity?

13. Quantifying manure entering flush stream vs. stay in corrals and other areas.

Comment on how much of the manure produced by the animals enters the flush stream versus stays in semisolid form in the corrals or other areas. Is there a specific category of cows (such as dry cows or heifers) whose manure is left out of the flush stream? Does the amount of manure that enters the flush stream change depending on the season. For example, in the winter does more manure enter the flush stream because all the cows locked into the barns versus others seasons. Be descriptive and provide specific scenarios.

14. Separator technology (type, manufacturer, screen size).

15. Separator accessory equipment size and number (pumps, agitators, agitator-pumps).

16. Number of years of system operation and dates and reasons for any modifications.

17. Infrastructure capital costs (separator and accessory equipment, processing pit, retrofits, concrete, etc.).

18. Frequency of processing pit, settling pond, lagoon, separator cleaning.

DAIRYING SYSTEM

19. Acreage of dairy land.

How many acres dairyed at the dairy site? Any acres dairyed offsite to support the dairy?

20. Types of fertilizer application.

Lagoon water, separated solids, manure from corrals, solids from bottom lagoon, other sources?

21. **Acreage accessible by lagoon irrigation.**
    Acres that get manure water applied from lagoon.

22. **Crop rotations and seasons.**

SOLIDS MANAGEMENT & BEDDING

23. **Describe the various end uses of separator manure solids?**

24. **How are separated solids handled and processed in preparation for each end use?**

25. **During advanced solar drying of separated solids what is the length of time of processing and is there a target temperature?**

26. **How does this processing vary throughout the year based on weather conditions and season?**

27. **Does separator provide excess, just enough, or not enough material for use on the dairy? Does the dairyer wish they had more? If they would like more, what would they use them for?**

28. **Do separated solids provide all of the bedding needs on the dairy or does the dairyer have to purchase extra materials for bedding?**

29. **If there were or are enough separator solids to cover bedding purposes, does/would the dairyer still amend bedding, either continuously or at various times during the year, with other materials?**

30. **Is bedding continuously amended with other materials or just at specific times of the year. What are those materials, in what ratios are they added into the bedding, and why are they added?**

31. **What are excess separator solids used for on your dairy? Are separated solids ever exported off the dairy? If yes, to who, and for what use? Is data on solids exporting tracked?**

32. **Is bedding produced all year round or only during the dry summer months? Does bedding composition vary based on weather conditions and season?**

33. **How are aged bedding and freshly separated solids handled in the cold and wet weather months?**

34. If the dairy has corrals, how often do corrals get manure scraped? What happens with that manure and how is it handled over the course of the year?

35. If there are manure solids from the settling pond or lagoon that is dredged out, how often does that happen and how are those solids used and handled?

36. Is bedding ever added to corrals?

37. How often is bedding added to the barns? Every week? 2 weeks? Month? Is that addition of bedding pretty regular or does it vary?

38. What is done with exceed feed at the end of the day? Is it combined and used for bedding material?

SAMPLING EVENT SPECIFIC DATA

QUARTER 1, SUMMER.

39. Herd size (milking, dry, heifer).

40. Herd location and quantifying manure in the lanes (freestalls, corrals, or elsewhere).

41. Feed composition and daily amount.
Any information on feed composition and daily amount consumed per cow.

42. Bedding composition and amount.
Any information on bedding composition and amount added per day.

QUARTER 2, FALL.

43. Herd size (milking, dry, heifer).

44. Herd location and quantifying manure in the lanes (freestalls, corrals, or elsewhere).

45. Feed composition and daily amount.
Any information on feed composition and daily amount consumed per cow.

46. Bedding composition and amount.
Any information on bedding composition and amount added per day.

QUARTER 3, WINTER.

47. Herd size (milking, dry, heifer).

48. Herd location and quantifying manure in the lanes (freestalls, corrals, or elsewhere).

49. Feed composition and daily amount.
Any information on feed composition and daily amount consumed per cow.

50. Bedding composition and amount.
Any information on bedding composition and amount added per day.

QUARTER 4, SPRING.
51. Herd size (milking, dry, heifer).

52. Herd location and quantifying manure in the lanes (freestalls, corrals, or elsewhere).

53. Feed composition and daily amount.
Any information on feed composition and daily amount consumed per cow.

54. Bedding composition and amount.
Any information on bedding composition and amount added per day.

Appendix B. Nutrient Analysis

Table B1. pH and concentration of elements (w.b.*) in the liquid streams for Dairy A

		Summer		Fall		Winter		Spring	
Parameter	**Units**	**Inlet**	**Outlet**	**Inlet**	**Outlet**	**Inlet**	**Outlet**	**Inlet**	**Outlet**
pH	pH units	6.90	7.30	7.40	7.50	7.40	7.60	7.10	7.30
Ammonia Nitrogen	mg/L	259.00	299.50	339.00	339.00	627.00	694.00	308.00	300.00
Soluble salts	mg/L	3905.00	3800.00	4200.00	4200.00	6590.00	6590.00	4000.00	3880.00
Magnesium	mg/L	95.40	87.85	87.70	80.80	123.00	122.00	145.00	146.00
Calcium	mg/L	136.00	135.00	235.00	228.00	400.00	418.00	373.00	383.00
Boron	mg/L	0.40	0.37	0.84	0.79	1.13	1.16	0.62	0.51
Sodium	mg/L	288.50	285.00	278.00	269.00	521.00	532.00	349.00	373.00
Potassium	mg/L	536.00	540.00	660.00	639.00	1170.00	1190.00	720.00	757.00
Total Kjeldahl Nitrogen	mg/L	711.00	579.50	554.00	554.00	1200.00	1180.00	661.00	633.00
Total Phosphorus	mg/L	61.60	54.75	64.00	58.50	116.00	114.00	225.00	251.00
EC	mmhos/cm	6.10	5.94	6.57	6.56	10.30	10.30	6.25	6.07

* Wet basis

Table B2. pH and concentration of elements in the solid streams for Dairy A

Parameter	**Unit**	**Summer**	**Fall**	**Winter**	**Spring**
Moisture contents	% w.b.	80.50	82.10	83.10	78.70
Total solids	% w.b.	19.50	17.90	16.90	21.30
pH	pH units	7.40	7.90	8.30	7.70
Soluble Salts	mg/kg wet	1185.00	1250.00	2450.00	1040.00
Copper	mg/kg wet	56.90	27.70	23.00	69.40
Zinc	mg/kg wet	154.50	115.00	87.60	128.00
Manganese	mg/kg wet	97.95	78.60	59.70	71.40
Iron	mg/kg wet	2605.00	1490.00	1040.00	1530.00
Boron	mg/kg wet	27.90	25.60	22.30	24.60
Electrical conductivity	mmhos/cm	1.86	1.95	3.83	1.63
Sulfur	%, d.b.	0.39	0.34	0.25	0.32
Total phosphorus	%, d.b.	0.35	0.33	0.27	0.30
Total nitrogen	%, d.b.	1.97	1.57	1.86	0.71
Magnesium	%, d.b.	0.42	0.35	0.28	0.34
Calcium	%, d.b.	1.70	1.49	1.08	1.31
Sodium	%, d.b.	0.21	0.21	0.32	0.18
Potassium	%, d.b.	0.45	0.57	0.77	0.45

Table B3. pH and concentration of elements (w.b.) in the liquid streams for Dairy B

Parameter	Units	Summer			Winter			Spring		
		Inlet	Midpoint	Outlet	Inlet	Midpoint	Outlet	Inlet	Midpoint	Outlet
pH	pH units	6.70	6.90	6.90	7.40	7.70	7.40	6.80	7.10	7.70
Ammonia Nitrogen	mg/L	297.00	311.00	314.00	1020.00	977.00	932.00	473.00	482.00	490.00
Soluble salts	mg/L	4400.00	4390.00	4340.00	8960.00	8900.00	8510.00	5840.00	5670.00	5630.00
Magnesium	mg/L	152.00	135.00	130.00	264.00	258.00	235.00	248.00	228.00	217.00
Calcium	mg/L	180.00	168.00	163.00	479.00	469.00	419.00	410.00	390.00	449.00
Boron	mg/L	1.05	0.88	0.85	2.27	2.20	2.03	1.52	1.45	1.53
Sodium	mg/L	314.00	256.00	250.00	540.00	518.00	473.00	415.00	411.00	337.00
Potassium	mg/L	717.00	644.00	626.00	1730.00	1660.00	1510.00	1310.00	1290.00	1080.00
Total Kjeldahl Nitrogen	mg/L	980.00	918.00	834.00	1850.00	1780.00	1760.00	1120.00	1140.00	1080.00
Total Phosphorus	mg/L	79.00	70.00	66.80	138.00	137.00	124.00	274.00	203.00	236.00
EC	mmhos/cm	6.88	6.86	6.78	14.00	13.90	13.30	9.13	8.86	8.80

Table B4. pH and concentration of elements in the solid stream in both piles for Dairy B

Parameter	Unit	Summer		Winter		Spring	
		Pile 1	Pile 2	Pile 1	Pile 2	Pile 1	Pile 2
Moisture contents	% wb	75.5	76	78.2	76.8	76	73.9
Total solids	% wb	24.5	24	21.8	23.2	24	26.1
pH	pH units	7	7.5	8.4	8.5	7.9	8.2
Soluble Salts	mg/kg wet	1660	1580	1840	1640	1820	1700
Copper	mg/kg wet	45.4	58.3	34.6	54	65.8	104
Zinc	mg/kg wet	105	122	63.4	78.3	83.9	91.1
Manganese	mg/kg wet	71.8	83	48.7	66.9	64	72.5
Iron	mg/kg wet	1330	1580	709	1240	1410	1610
Boron	mg/kg wet	46.4	41.2	42.7	36.9	29.2	31.4
Electrical conductivity	mmhos/cm	2.59	2.47	2.87	2.56	2.84	2.65
Sulfur	%, db	0.29	0.32	0.2	0.22	0.24	0.26
Total phosphorus	%, db	0.223	0.263	0.169	0.202	0.227	0.235
Total nitrogen	%, db	2.07	2.26	1.47	1.69	0.94	0.87
Magnesium	%, db	0.42	0.463	0.296	0.332	0.33	0.368
Calcium	%, db	1.32	1.49	0.908	1.09	1.05	1.2
Sodium	%, db	0.14	0.156	0.239	0.206	0.146	0.13
Potassium	%, db	0.386	0.429	0.839	0.727	0.558	0.49

Table B5. pH and concentration of elements (w.b.) in the liquid streams for Dairy C

Parameter	Units	Summer			Fall			Winter			Spring		
		Inlet S1	Inlet S2	Outlet S2	Inlet S1	Inlet S1	Inlet S1	Inlet S1	Inlet S2	Outlet S2	Inlet S1	Inlet S2	Outlet S2
pH	pH units	7.50	7.20	7.40	7.40	7.40	7.50	7.00	6.50	6.90	7.20	6.70	7.10
Ammonia Nitrogen (wb)	mg/L	414.00	378.00	440.00	417.00	445.00	420.00	484.00	535.00	473.00	414.00	420.00	448.00
Soluble Salts (wb)	mg/L	4490.00	4600.00	4410.00	5250.00	5470.00	5200.00	5540.00	5780.00	5600.00	5090.00	5200.00	4950.00
Magnesium (wb)	mg/L	76.90	108.00	66.80	135.00	162.00	152.00	185.00	242.00	141.00	208.00	282.00	263.00
Calcium (wb)	mg/L	142.00	172.00	125.00	273.00	376.00	365.00	375.00	533.00	230.00	407.00	635.00	667.00
Boron (wb)	mg/L	0.09	0.12	0.10	1.09	1.21	1.16	1.00	1.29	1.37	0.64	1.06	0.93
Sodium (wb)	mg/L	363.00	358.00	355.00	329.00	360.00	335.00	327.00	334.00	382.00	274.00	304.00	286.00
Potassium (wb)	mg/L	904.00	897.00	883.00	832.00	919.00	853.00	788.00	816.00	925.00	917.00	1040.00	967.00
Kjeldahl Nitrogen (wb)	mg/L	470.00	879.00	868.00	739.00	778.00	778.00	1030.00	1380.00	1160.00	885.00	1200.00	1080.00
Total Phosphorus (wb)	mg/L	60.00	95.10	49.70	57.40	71.50	78.10	148.00	211.00	163.00	299.00	365.00	419.00
EC (wb)	mmhos/cm	7.02	7.19	6.89	8.20	8.55	8.12	8.65	9.03	8.75	7.95	8.12	7.74

Table B6. pH and concentration of elements in the solid stream in both piles for Dairy C

Parameter	Unit	Summer		Fall		Winter		Spring	
		Pile 1	Pile 2	Pile 1	Pile 1	Pile 1	Pile 2	Pile 1	Pile 2
Total solid	% wb	22.4	24.2	21.4	20	21.9	20.6	23.6	19.6
Moisture contents	% wb	77.6	75.8	78.6	80	78.1	79.4	76.4	80.4
pH	pH units	7.1	7.0	7.9	8.1	8	8	7.7	7.8
Soluble salts	mg/kg wet	1260.0	940.0	1660	1540	947	1170	1290	1580
Copper	mg/kg wet	39.6	33.9	24.3	28.5	15.1	24.8	43.6	47.2
Zinc	mg/kg wet	95.4	65.7	64.8	92.7	47.3	68.5	68.5	81.5
Manganese	mg/kg wet	85.2	69.3	76.4	93.1	39.2	69.8	74.9	81.7
Iron	mg/kg wet	1830.0	1340.0	1220	1810	735	1610	1530	2130
Boron	mg/kg wet	19.4	15.4	20.8	30.8	17.1	24.3	19.9	19.9
Electrical conductivity	mmhos/cm	2.0	1.5	2.6	2.4	1.48	1.83	2.02	2.47
Sulfur	%, db	0.3	0.3	0.26	0.3	0.2	0.27	0.32	0.3
Total phosphorus	%, db	0.3	0.2	0.209	0.255	0.164	0.228	0.253	0.278
Total Nitrogen	%, db	1.6	1.3	1.68	1.88	1.53	1.76	0.85	0.96
Magnesium	%, db	0.4	0.3	0.335	0.41	0.225	0.306	0.38	0.388
Calcium	%, db	1.3	1.0	1.07	1.32	0.797	1.35	1.14	1.29
Sodium	%, db	0.2	0.1	0.159	0.186	0.146	0.161	0.121	0.127
Potassium	%, db	0.507	0.433	0.511	0.556	0.405	0.452	0.48	0.511

Table B7. pH and concentration of elements (w.b.) in the liquid streams for Dairy D

		Winter		**Spring**	
Parameter	**Units**	**Inlet**	**Outlet**	**Inlet**	**Outlet**
pH	pH units	7.70	7.70	7.60	7.80
Ammonia Nitrogen	mg/L	596.00	591.00	524.00	510.00
Soluble salts	mg/L	6530.00	6390.00	6530.00	6720.00
Magnesium	mg/L	229.00	206.00	202.00	208.00
Calcium	mg/L	461.00	409.00	326.00	332.00
Boron	mg/L	1.50	1.31	1.41	1.46
Sodium	mg/L	322.00	286.00	350.00	362.00
Potassium	mg/L	1620.00	1470.00	1690.00	1750.00
Total Kjeldahl Nitrogen	mg/L	1080.00	1060.00	868.00	879.00
Total Phosphorus	mg/L	274.00	257.00	194.00	186.00
EC	mmhos/cm	10.20	9.98	10.20	10.50

Table B8. pH and concentration of elements in the solid streams for Dairy D

Parameter	**Unit**	**Winter**	**Spring**
Moisture contents	% w.b.	81.9	81.5
Total solids	% w.b.	18.1	18.5
pH	pH units	8.3	8.4
Soluble Salts	mg/kg wet	1480	2050
Copper	mg/kg wet	22.3	136
Zinc	mg/kg wet	81.8	87.7
Manganese	mg/kg wet	57	60.3
Iron	mg/kg wet	659	694
Boron	mg/kg wet	27	30.2
Electrical conductivity	mmhos/cm	2.32	3.21
Sulfur	%, d.b.	0.25	0.27
Total phosphorus	%, d.b.	0.241	0.231
Total nitrogen	%, d.b.	0.8	0.92
Magnesium	%, d.b.	0.267	0.29
Calcium	%, d.b.	0.846	0.868
Sodium	%, d.b.	0.136	0.172
Potassium	%, d.b.	0.733	0.873

Table B9. pH and concentration of elements (w.b.) in the liquid streams for Dairy E

Parameter	Units	Cell 1		Cell 2	
		Inlet	**Outlet**	**Inlet**	**Outlet**
pH	pH units	6.80	6.80	6.80	6.90
Ammonia Nitrogen	mg/L	294.00	297.00	332.00	307.00
Soluble salts	mg/L	3280.00	3240.00	3400.00	3360.00
Magnesium	mg/L	97.10	96.80	97.10	93.10
Calcium	mg/L	144.00	150.00	135.00	147.00
Boron	mg/L	1.75	1.76	1.60	1.70
Sodium	mg/L	237.00	239.00	260.00	261.00
Potassium	mg/L	611.00	595.00	615.00	605.00
Total Kjeldahl Nitrogen	mg/L	588.00	546.00	647.00	566.00
Total Phosphorus	mg/L	113.00	107.00	120.00	102.00
EC	mmhos/cm	5.13	5.06	5.31	5.25

Table B10. pH and concentration of elements in the solid streams for Dairy E

Parameter	Unit	Cell 1	Cell 2
Moisture contents	% w.b.	76.7	69
Total solids	% w.b.	23.3	31
pH	pH units	5.6	5.8
Soluble salts	mg/kg wet	2940	2570
Copper	mg/kg wet	44.5	38
Zinc	mg/kg wet	165	157
Manganese	mg/kg wet	127	127
Iron	mg/kg wet	2390	2630
Boron	mg/kg wet	35.4	30.9
Electrical conductivity	mmhos/cm	4.6	4.01
Sulfur	%, d.b.	0.39	0.4
Total phosphorus	%, d.b.	0.179	0.177
Total nitrogen	%, d.b.	0.82	0.78
Magnesium	%, d.b.	0.233	0.237
Calcium	%, d.b.	0.777	0.769
Sodium	%, d.b.	0.108	0.102
Potassium	%, d.b.	0.384	0.312

Table B11. pH and concentration of elements (w.b.) in the liquid streams for Dairy F

Parameter	Units	Fall		Winter		Summer	
		Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
pH	pH units	7.20	7.30	7.50	7.50	7.40	7.50
Ammonia Nitrogen	mg/L	479.00	484.00	440.00	462.00	364.00	364.00
Soluble salts	mg/L	5520.00	5400.00	5370.00	5380.00	4350.00	4310.00
Magnesium	mg/L	141.00	150.00	127.00	132.00	146.00	137.00
Calcium	mg/L	230.00	262.00	254.00	271.00	260.00	242.00
Boron	mg/L	1.37	1.69	1.31	1.36	0.91	0.88
Sodium	mg/L	381.00	415.00	331.00	336.00	345.00	337.00
Potassium	mg/L	925.00	1020.00	1000.00	1030.00	858.00	830.00
Total Kjeldahl Nitrogen	mg/L	857.00	829.00	750.00	773.00	622.00	599.00
Total Phosphorus	mg/L	83.60	84.10	60.60	66.40	189.00	214.00
EC	mmhos/cm	8.62	8.44	8.39	8.41	6.79	6.74

Table B12. pH and concentration of elements in the solid streams for Dairy F

Parameter	Unit	Fall	Winter	Summer
Moisture contents	% w.b.	75.8	76.8	75.7
Total solids	% w.b.	24.2	23.2	24.3
pH	pH units	8.1	7.8	7.8
Soluble Salts	mg/kg wet	1150	1660	1030
Copper	mg/kg wet	12.1	8.24	14.8
Zinc	mg/kg wet	71.6	61.3	73
Manganese	mg/kg wet	63.6	45.2	47.5
Iron	mg/kg wet	1510	841	1050
Boron	mg/kg wet	20.4	30.7	20.9
Electrical conductivity	mmhos/cm	1.79	2.6	1.61
Sulfur	%, d.b.	0.23	0.23	0.26
Total phosphorus	%, d.b.	0.22	0.181	0.194
Total nitrogen	%, d.b.	1.69	1.57	0.72
Magnesium	%, d.b.	0.269	0.241	0.258
Calcium	%, d.b.	1.14	0.879	0.941
Sodium	%, d.b.	0.172	0.153	0.131
Potassium	%, d.b.	0.5	0.554	0.402