Third-Party Monitoring and Verification of a Farm-Scale Anaerobic Digester

September 2023

Prepared by
Dr. Stephanie Lansing, slansing@umd.edu
Dr. Amro Hassanein, ahassane@umd.edu
Kirkland Mahoney, kmahone4@umd.edu
University of Maryland
Department of Environmental Science & Technology
College Park MD 20742

Prepared for
Maryland Department of Agriculture
50 Harry S. Truman Pkwy
Annapolis, MD 21401

Table of Contents

1. Executive Summary

Anaerobic digestion (AD) is a four-stage microbial process that utilizes a consortium of microorganisms to break down organic matter and produce renewable energy. Anaerobic digestion can be applied to various waste sources. Anaerobic digestion of food waste with dairy manure results in increased energy production and reduces greenhouse gas (GHG) emissions from storage of food waste and dairy manure in landfills and open-air lagoons, respectively. The Maryland Animal Waste Technology Fund provides incentives to demonstrate innovative technologies for managing animal manure, including technologies that generate energy from animal manure, reduce impacts of on-farm nutrient management, and repurpose manure by creating marketable products.

Kilby Farm received funding to demonstrate anaerobic co-digestion of dairy manure (DM) and pre-consumer food waste (dissolved air flotation waste (DAF), cranberry processing waste, and milk waste) to produce on-farm energy and generate compost from DM solids in a composting facility. The University of Maryland (UMD) evaluated the anaerobic digestion and the composting facility project over a 13-month period. UMD also calculated the sustainability of the current system compared to traditional DM management in Maryland using a life cycle assessment (LCA) approach. Monthly samples were collected from nine sampling points (six liquid samples and three solid samples) and energy production was monitored to determine the operational mass and energy balances and calculate sustainability using the LCA framework.

Over a 13-month period, the total solids (TS) and volatile solids (VS) of each substrate, including DAF, cranberry waste, and DM before and after solids separation (SS) was quantified. The TS for DAF and cranberry were 11.6% and 20.1%, respectively, and 5.72% for the combined DAF, cranberry and liquid DM digester influent. The TS for liquid DM ranged from 2.53 to 2.75%. The VS for the DAF and cranberry wastes were 10.9% and 19.4%, respectively, which equates to 93% and 96% VS based on dry matter (DM). The VS of separated liquid DM ranged from 1.7 to 1.9% (71% VS based on DM). The combined influent had a VS of 5.0% (87.4% VS based on DM), highlighting the benefit of co-digesting food waste, with a high VS with the lower VS in the DM to enhance biogas generation.

The yearly biogas production from the AD system was 1,831,450 m^3/yr, with 72.2% consumed in the combined heat and power (CHP) electric generation system and 27.8% flared. The average methane (CH_4) concentration in the biogas was 56.2% resulting in 1,027,444 m^3 CH_4/year, with little variation observed over the 13-months. The CHP generated an average of 224 kW per hour, just below its maximum capacity of 240 kWh. The average daily kWh production of the CHP was 5,378 kWh, resulting in an output of 1,983,722 kWh per year.

The average total nitrogen (TKN) concentration for DAF and cranberry was 4,170 mg N/L and 2,840 mg N/L, respectively, while the DM ranged from 1,860 to 1,950 mg N/L. The total phosphorous (TP) concentration for DAF and cranberry was 870 mg-P/L and 500 mg-P/L, respectively, and the DM ranged from 300 to 450 mg-P/L. The liquid effluent was surface applied and injection. The ammonia (NH_3) volatilization from injection of liquid manure fertilizer application found no NH_3 emissions (below the detectable limit), while one hour after surface application there was a concentration of 4.27 mg NH_3 N/L, with 5.27 mg NH_3-N/L after three hours, and 16.40 NH_3-N/L after 24 hours.

The digester operated under mesophilic conditions, with an average temperature of 36.3°C, within the temperature conditions for optimal mesophilic digestion. The pH values varied across substrates, with cranberry having the lowest average pH (3.6), and the AD effluent having the highest average pH (7.90). The high biogas production shows that the pH of the three co-substrates was circum-neutral during digestion and no adverse effects were seen.

A lab-scale biomethane potential (BMP) test was performed to evaluate the energy production of the substrates used at Kilby Farm. Substrates were digested individually and in combination to test the efficiency of co-digestion and mono-digestion of each substrate. Co-digestion of DAF, cranberry, and all dairy manure (no solid separation) produced had the highest digestion efficiency based on the organics (VS) entering the digester (987 L CH_4/kg VS), which was similar efficiency to the mixture of substrates used on farm (DM after SS, cranberry and DAF), at 958 L CH_4/kg VS. The BMP results had higher CH_4 conversion efficiency compared to the 13-month study of on-farm CH_4 production (631 L CH_4/kg VS), which is expected due to the ideal lab conditions utilized. The DAF and cranberry wastes digested singularly had higher cumulative CH_4 production (909 mL CH_4 for cranberry, 922 mL CH_4 for DAF) than the on-farm mixture (866 mL CH_4), but the efficiency was lower without the DM, which moderates the low pH of the food waste substates.

Total solids (TS) entering the system decreased by 50% (input: 1,672 tons TS/yr; output: 843 metric tons TS/year), and volatile solids were decreased by 58% (input: 1,441 metric tons VS/yr; output: 606 metric tons VS/yr). During solid separation, 4,703 m^3 of solids were separated from the liquid DM annually. The separated solids underwent composting, with twice a week turning to promote aerobic microbial processes. The final compost contained 1.2% total N, 0.24% P, and 0.43% K. This equates to 50.9 metric tons of N, 10.1 metric tons of P, and 18.2 metric tons of K per year in compost from the DM separated solids.

A life cycle assessment (LCA) was performed to analyze the farm-scale AD system under five operating scenarios: 1) baseline scenario without anaerobic digestion, DM solids separation, or composting: 2) the current condition of the farm-scale AD system (anaerobic digestion and composting of the separated DM solids); 3) DM and FW co-digestion with no DM solids separation and composting (Scenario A); 4) DM mono-digestion with DM solids separation and composting (Scenario B); 5) DM mono-digestion with no DM solids separation and composting (Scenario C). Compared to the baseline scenario, the current condition has the largest reductions in environmental impacts from acidification (320%), eutrophication (447%), carcinogens (42%), and ecotoxicity (347%). The current condition (-65 T N eq/yr) removed 442% of N. Furthermore, the current condition reduced the CO_2 emissions by over 81% (4,495 T CO_2 eq/yr) compared to the baseline scenario (23,751 T CO_2 eq/yr, 19 T N eq/yr).

Overall, the Kilby digester decreased the GHG emissions drastically while generating a substantial amount of electricity. By employing anaerobic digestion and composting at Kilby farm, 20,000 tons of CO_2 are removed every year compared to open lagoon storage of manure and FW. Additionally, the nearly 2,000,000 kWh of annual electricity produced equates to enough energy to power 190 homes each year. With the added benefit of solid separation, the production of 4,245 metric tons of compost created an additional renewable source of recycled nutrients that can be used for fertilization and sold off-farm as a value-added component. The liquid digester effluent was used as fertilizer for crop application, with elimination of ammonia emissions when manure injection was used. Overall, the current system at Kilby farm proved to be the most efficient with the most reductions in environmental impact from open lagoon manure storage. Reducing the transportation distances for the food processing waste substrates would yield additional environmental reductions.

2. Kilby Farm Anaerobic Digestion and Composting System Description

Anaerobic digestion (AD) is a series of microbial processes that transform biodegradable material in the absence of oxygen into methane (CH_4)-enriched biogas. Biogas can be produced from a variety of organic materials including dairy manure, food waste, crop waste, or sewage sludge. The Kilby Farm anaerobic digestion system consisted of a sand separation lane, solids-liquid separation unit, covered lagoon digester, H_2S scrubber, combined heat and power (CHP) electric generator (240 kWh, Siemens, Germany), food waste (FW) storage tanks, and an open digester effluent storage lagoon.

The system operation was as follows: 1) the dairy manure (DM) from 750 head of cattle was washed from the barn onto an angled concrete slab for sand separation. Sand separation resulted in the sand bedding material being removed from the liquid waste stream, while the liquids were piped towards the separation unit; 2) the DM was processed initially through a screw-press system, then through a Sweco solid-separation unit to separate the solids and the liquids via a screen and vibrator, where the solids (4,703 m^3/yr) were transferred to an on-site composting facility; 3) the liquid DM (64,285 L/day, 74% of volume) was pumped into the covered lagoon digester (96 m long by 24 m wide, ~2,476 m^2) and mixed with FW consisting of poultry litter processing dissolved air flotation (DAF) (16,071 L/day 18.5% of volume), cranberry processing waste (3,214 L/day 3.7% of volume), and milk waste (3,214 L/day, 3.7% of volume) fed continuously via a 240-V pump (Gormann-Rupp, 13A20-B, Mansfield, Ohio) operating 24 hours per day; 4) liquid effluent leaving the AD was stored in an open lagoon before being applied to fields as a fertilizer bi-annually (fall and spring); 5) biogas was processed through the H_2S scrubbing system before being burned in the CHP to produce electricity or burned at a flare; 6) DM solids separated by the solids separation unit were composted, with compost pile turning twice per week. Captured heat from the CHP generator was recirculated and used to heat the digester.

The FW consisted of DAF waste from poultry processing, milk waste, and cranberry processing waste delivered to the farm and stored in 375,000-liter concrete pits, with agitation completed before injection into the system. The produced biogas was composed of 50-65% CH_4, the energy source, as well as CO_2 (35-50%) water vapor (3-4%), and hydrogen sulfide (H_2S: 500 – 3,000 ppm, <0.3%). Dairy manure consisted of ~70% liquid and 30% solids when cleaned out of barns (Figure 1). Following digestion treatment, the liquid, nutrient-rich slurry was field applied as a fertilizer to grow crops for feeding the dairy cows.

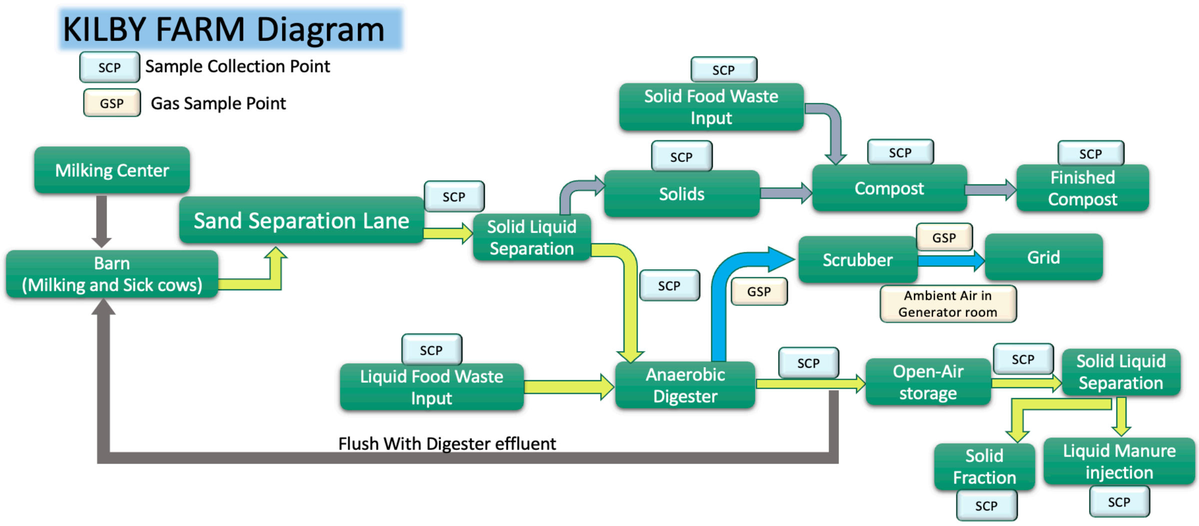

Figure 1: The solid, liquid, and gas sampling points for the AD and composting facilities.

3. Project Monitoring

The University of Maryland (UMD) monitored the anaerobic digestion and nutrient capture demonstration project over a 13-month sampling period and calculated its environmental impact using a life cycle assessment (LCA) approach. From August 2021 to December 2022, UMD personnel collected monthly samples from nine different sampling points, including six liquid samples, three solid samples, and two gas samples to track solids, organics, and nutrient transformations during the anaerobic digestion and nutrient capture processes and verify energy production values. The solid and liquid samples were analyzed for total solids (TS), volatile solids (VS), chemical oxygen demand (COD), soluble COD (sCOD), volatile fatty acids (VFAs), pH, total Kjeldahl nitrogen (TKN), total phosphorus (TP), and ammonium-nitrogen (NH_4^+-N). The biogas was continually tracked for quantity and analyzed for quality (percent CH_4, H_2S, and CO_2).

For the laboratory analysis of liquid and solid samples, pH was measured using a glass electrode Accumet AB 15 pH meter. Standard Methods for the Examination of Water and Wastewater[1] was used to determine total solids (TS: Method 2540B) and volatile solids (VS: Method 2540 E). The COD and sCOD concentration were measured using the digestion method adapted by HACH[2], with sCOD filtered through a 0.45µm membrane filter membrane prior to analysis. Ammonia samples were acidified with 15 N sulfuric acid to pH 2, acid extracted, filtered through 0.45µm membrane filter, and analyzed using a Lachat instrument (QuikChem Method 10-107-06-2-O). The TKN and TP samples were digested with 15 N sulfuric acid and $CuSO_4$*$5H_20$, filtered through 0.45µm membrane filter and analyzed on the Lachat (QuikChem Method 13-107-06-2-D for TKN and QuikChem Method 13-115-01-1-B for TP). For VFA determination, acidified (pH 2.0) samples were centrifuged for 20 min at 5,000 RPM, the supernatant was filtered to 0.22 µm, and the liquid filtrate analyzed for VFAs (acetate, propionic, valeric, and butyric acids) using a 7890A Agilent gas chromatograph. All samples were analyzed in triplicate and followed laboratory quality control and quality assurance procedures.

The in-line monitoring system measured the pH and temperature of the digesters, H_2S removal, biogas produced, biogas flared, biogas used in the generator, electricity generated, and electricity use. When technical problems arose with on-site sensors, Kilby Farm and Martin Machinery were contacted to resolve issues with monitoring data collected by UMD personnel. Additionally, UMD personnel shared laboratory-based data results with Kilby Farm to provide feedback, including analytical warning signs for any potential process failures, and data results that showed points for which parameter optimization to increase the system performance.

A comparative Life Cycle Assessment (LCA) was conducted to determine on-farm mass, energy, carbon, and nutrient balance and the effectiveness of the technology in reducing the cradle to grave environmental impacts. The LCA followed the ISO 14040 and 14044 standards. The LCA of the nutrients, energy, and carbon flows were performed using SimaPro software (Version 9.0) developed by PreConsultants. The environmental impacts were estimated using the ReCiPe 1.10/World midpoint (H) impact assessment method. There were 10 LCA impact categories included in the analysis to determine the impacts of the technology implementation under different scenarios for greenhouse gas emissions, energy consumption and production, eutrophication, and human toxicity. The scope of the project was "from cradle to grave," defined as the manufacture of the digestion and nutrient capture infrastructure to the disposal of the system.

4. Detailed Project Monitoring Results

4.1 Biogas and Energy Production

The yearly biogas production from the AD was 1,831,450 m^3/yr. The majority of biogas (72.2%) was consumed in the CHP (1,322,306 m^3/yr) while 27.8% of the biogas was flared (509,134 m^3/yr). Based on the yearly biogas production, roughly 4.6*10^{10} BTUs were generated annually, with 3.3*10^{10} BTUs used in the CHIP and 1.2*10^{10} BTUs were flared and not utilized. The percent CH_4 in the biogas from the on-site biogas analyzer is shown in Figure 2A. During normal operation, the average CH_4 concentration was 56.2%. From Month 1 to 6 (Sept 2021 to Feb 2022), the average percent CH_4 in the biogas decreased to 54.1%, which increased to 60.1% from Month 6 to 13 (Feb 2022 to Sept 2022), and 63.2% from Month 13 to 16 (Sept 2022 to Dec 2022), with a decrease during the final month (Jan 2023) to 56.1% CH_4.

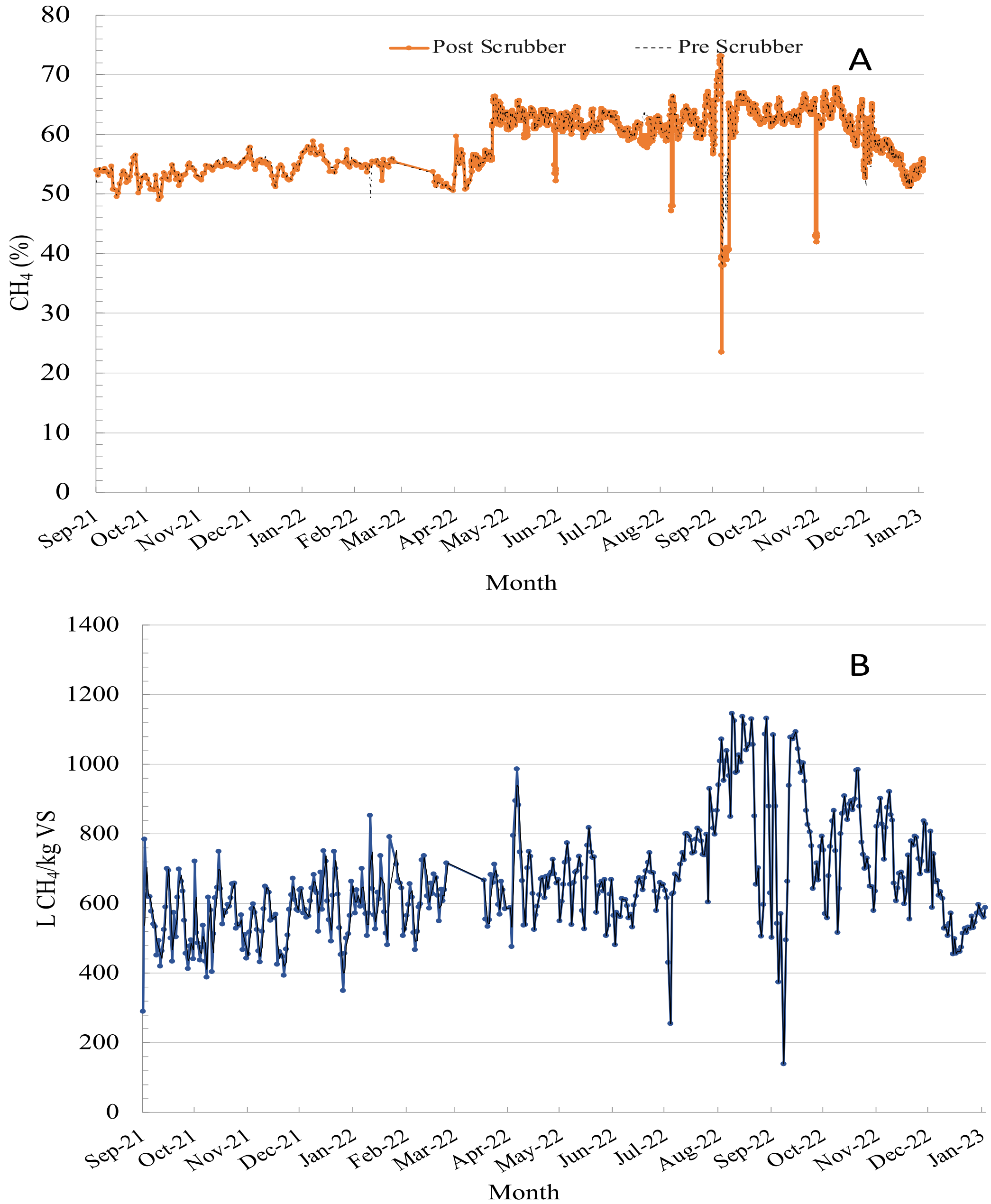

Figure 2: The percent methane (CH_4) in the produced biogas in (A) and CH_4 production normalized by the volatile solids (VS) in the digester influent in (B) from co-digestion of dairy manure and food waste.

Hydrogen sulfide (H_2S) is a byproduct of the AD process. As microorganisms utilize different substrates for respiration, H_2S is produced from biological substrates containing sulfur. When biogas with H_2S is combusted, it can be corrosive to metal materials and electric generation equipment. Scrubbing of H_2S from the biogas is recommended prior to using the biogas in a generator or broiler[3]. The recommended maximum H_2S concentration for biogas end uses are shown for boilers (1,000 ppm), engine-generator sets (500 ppm), vehicle fuel (23 ppm), pipeline injection (4 ppm), and fuel cells (1 ppm)[3]. Kilby Farm employs an iron-sponge H_2S scrubbing system. As the biogas exits the digester, it is passed through a large container holding iron shavings, and the H_2S binds to the iron forming iron sulfide (FeS), reducing the concentration of H_2S in the biogas.

During the monitoring period, the H_2S scrubbing system had an efficiency near 100%. The average concentration pre-scrubber was 212 ppm, while the average H_2S concentration post-scrubber was 4.4 ppm (Figure 3). Throughout most of the monitoring period, the H_2S concentration remained very low or at 0 ppm. In April 2022, there was a spike above 3000 ppm caused by a shutdown of the scrubbing system, not indicative of the regular operation of the system. However, in the last two months of monitoring (December 2022 and January 2023), there was a steady increase in H_2S concentration. It was determined that this was due to the decreasing efficacy of the scrubbing material over time as it was saturated with H_2S and it could be time for replacing of the iron filings inside the scrubber. Despite this, the concentration of H_2S remained low after the scrubbing system, within allowable limits for combustion.

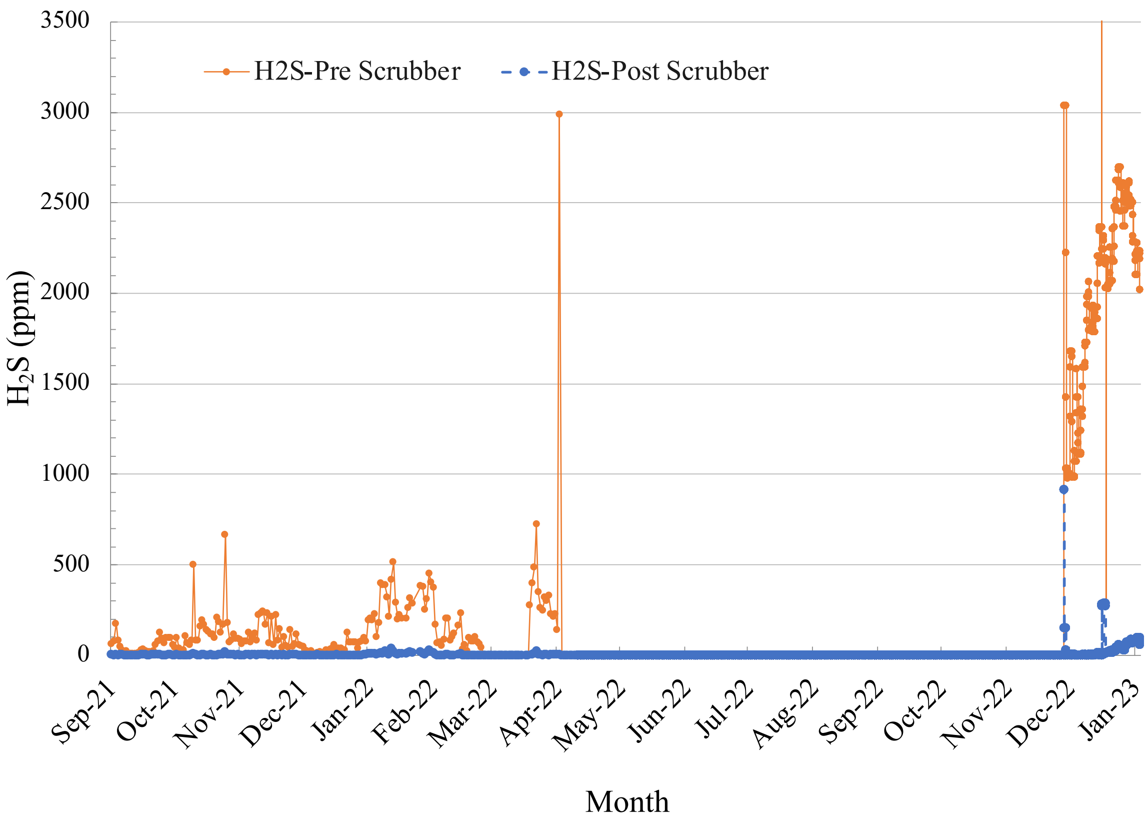

Figure 3: Hydrogen sulfide (H_2S) concentration in the biogas over the monitoring period.

The combustion of biogas in a CHP generates electricity that can either be returned to the system or sold for profit. The CHP at Kilby Farm had a maximum capacity of 230 kW/hr. The average kWh production of the CHP was 5,378 kWh/day, with an average energy production of 224 kW per hour, which was near the capacity of the generator (Figure 4). Over the monitoring period (Sept 2021 to Jan 2023), the CHP output was 1,983,722 kWh/yr.

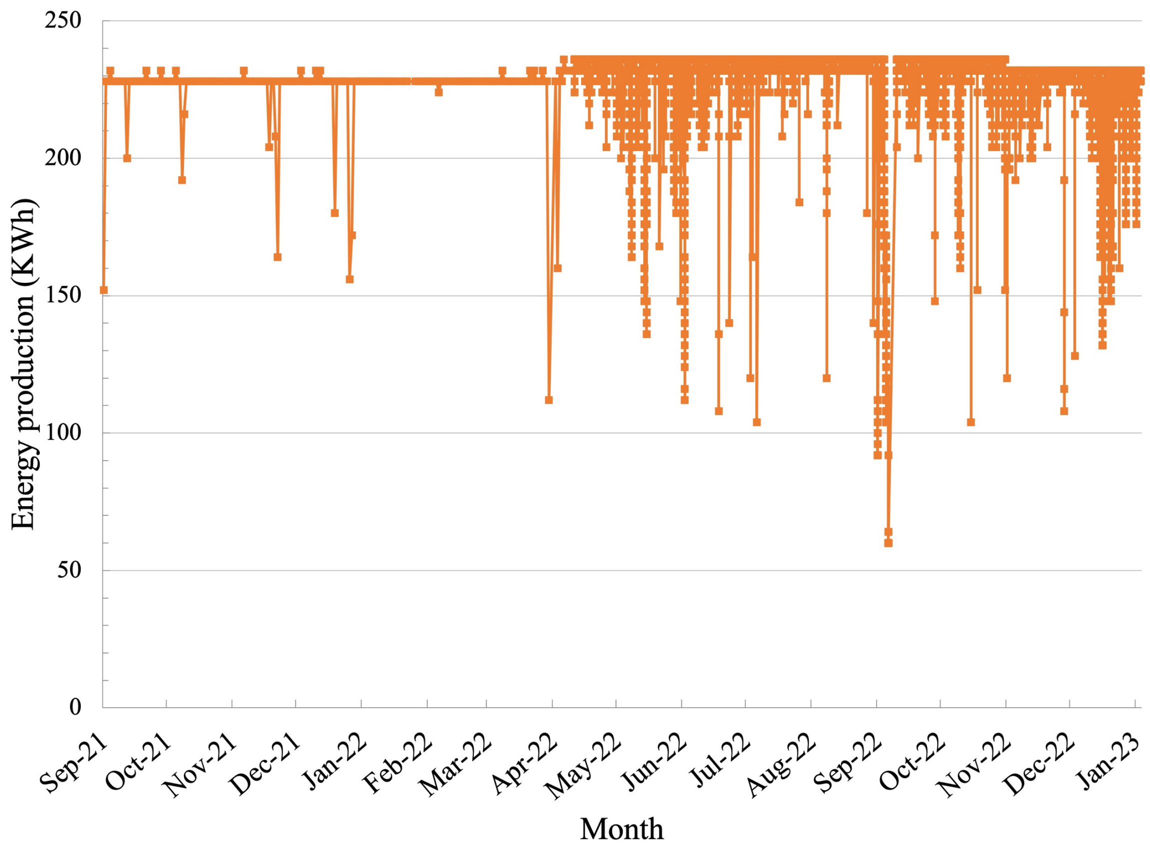

Figure 4: Energy production kWh from the combined heat and power (CHP) generator.

4.2 Total Solids (TS) and Volatile Solids (VS) Transformations

The average TS over the 13-month monitoring period for DAF and cranberry wastes were 11.6 ±2.27% and 20.1 ±3%, respectively (Figure 5A). The average TS for the dairy manure (DM) before solids separation (SS), DM after SS, DM digestion influent, and digester effluent were 2.75 ±0.18%, 2.59 ±0.16%, 2.53 ±0.16%, and 2.63 ±0.18, respectively. The DM digester influent represents the liquid DM entering the digester after solids removal. Expectedly, a decrease in TS was observed between the DM before SS and the DM after SS due to the removal of the DM solids (~27%).

The average VS for DAF and cranberry over 13 months were 10.9 ±2.26% and 19.4 ±3.04%, respectively, which equates to 93% and 96% VS based on dry matter (DM) (Figure 5B). The VS of separated liquid DM ranged from 1.7 to 1.9% (71% VS based on DM). The average VS over 13 months for the DM before SS and digester effluent were 1.9 ±0.16% and 1.8 ±0.14%, respectively. The combined digester influent (DM influent, DAF, cranberry) had a VS of 5.0 ±1.8% over the 13-month sampling period (87.4% VS based on DM), highlighting the benefit of co-digesting food processing waste with the lower-VS of the liquid dairy manure.

Energy production is directly related to the conversion of VS to CH_4. Combining the lower-VS DM with higher-VS cranberry and DAF positively impacted biogas generation. While increased biogas and CH_4 yield from the co-digestion of FW and DM can be expected, this research included a cranberry waste, a high-VS (and high sugar) substrate that has not been studied in farm-scale AD, and adding DAF waste is of great interest to the ability of anaerobic digestion to eliminate the odors associated with DAF field application.

The anaerobic digestion mass balance showed that the TS entering the system (1,672 metric tons TS/yr) decreased by 50% from influent to digester effluent (843 metric tons TS/year). Similarly, the VS entering the system (1,442 metric tons VS/yr) decreased by 58%, with lower values in the digester effluent due to the conversion to biogas (606 metric tons VS/yr). This mass balance represents a relatively high conversion efficiency, with 58% VS destruction in the system, leading to the high production of CH_4 (631 L CH_4/kg VS).

The field data showed that when the CH_4 production was normalized by the amount of organic material added to the digester, the average for the entire monitoring period (September 2021 to January 12^{th,} 2023) had a digestion efficiency of 631 L CH_4/kg VS (Figure 2B). This normalization by volatile solids (VS) provides information on the efficiency of the CH_4 production and converting the added organics (VS) to bioenergy, but does not indicate the overall energy production based on the volume of each substrate added to the system.

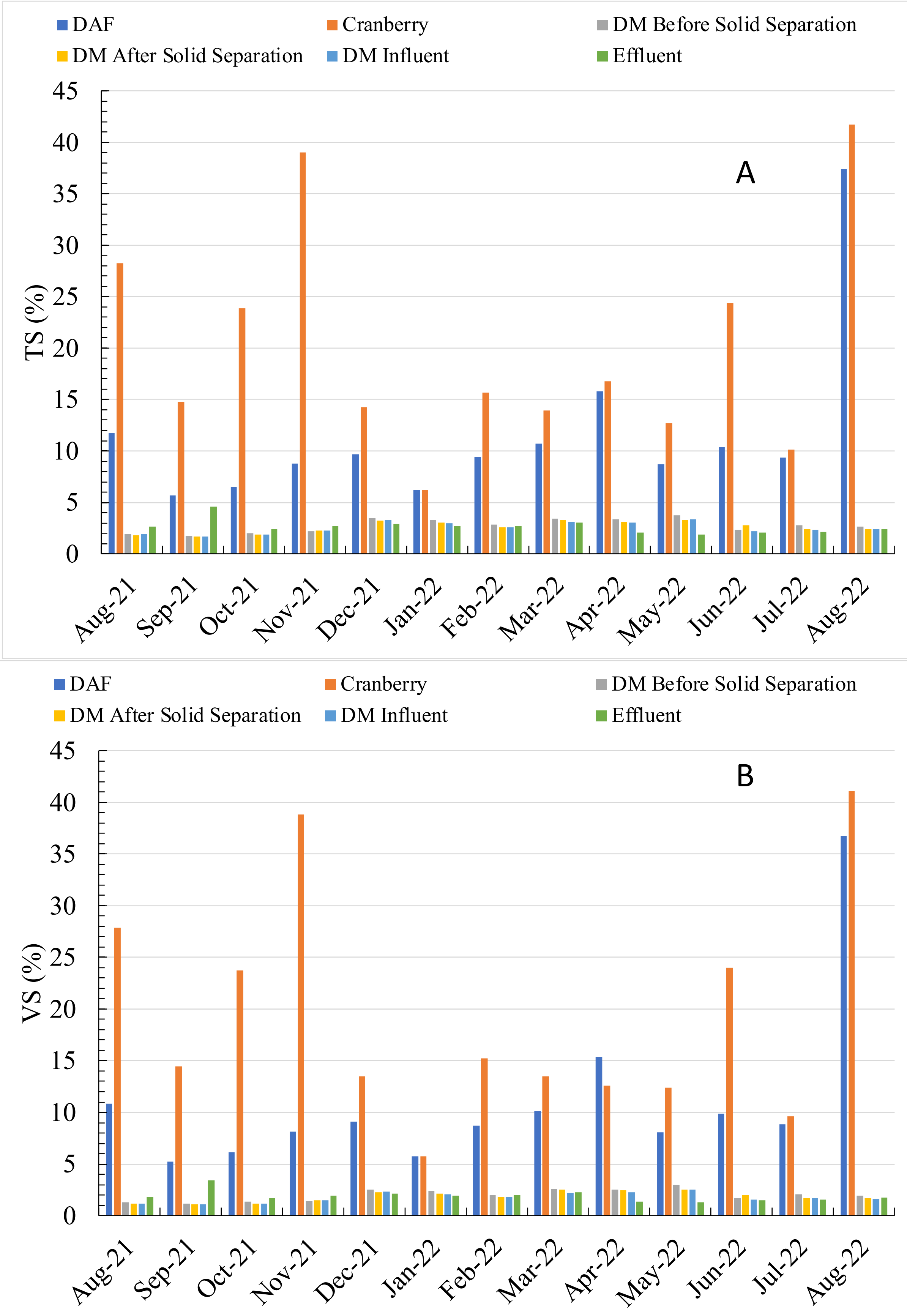

Figure 5: Total solids (TS%) over 13 months for liquid samples (A) and volatile solids (VS%) for liquid samples (B) over the sampling period.

4.3 Soluble Chemical Oxygen Demand (SCOD)

Soluble chemical oxygen demand (sCOD) represents the amount of organic matter in the specific substrates for biogas production, with values similar to VS, as microbial activity reduces the sCOD due to the methanogenesis converting the organic material to biogas. The average sCOD over 13 months for DAF and cranberry wastes were 26.7 ±4.5 g/L and 91.5 ±13.4 g/L, respectively (Figure 6). The average sCOD for the DM before SS, the DM after SS, the DM digester influent, and digester effluent over 13 months were 9.6 ±1.7 g/L, 6.5 ±1.1 g/L, 6.2 ±1.2 g/L, and 1.9 ±0.5 g/L respectively. The lowest substrate sCOD was DM influent. Cranberry had the highest average sCOD, indicating a high potential for microbial degradability and biogas generation when co-digested. The sCOD reduction (94%) between the influent and effluent represents a stable anaerobic digestion process, where a substantial amount of substrate is converted into combustible biogas.

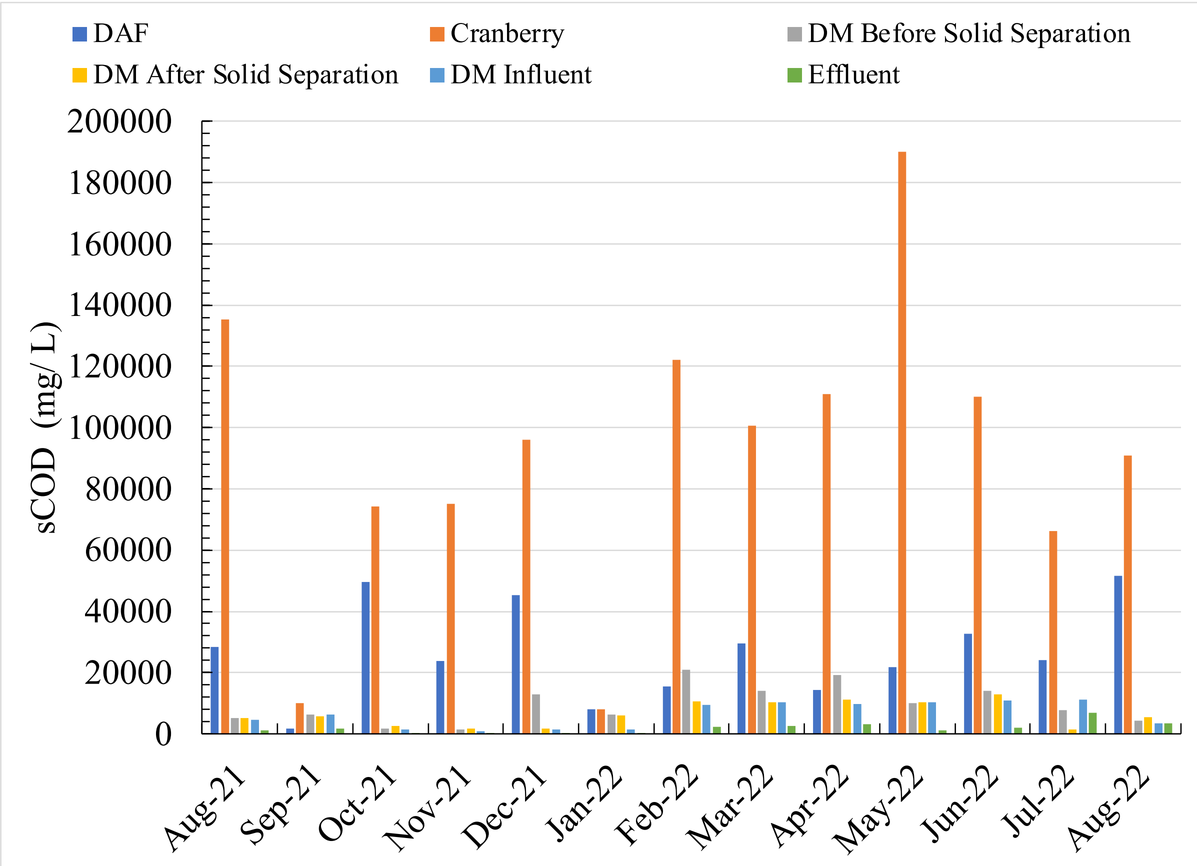

Figure 6: Soluble chemical oxygen demand (sCOD) for liquid samples over the sampling period.

4.4 Nutrient Transformations:

The ammonium (NH_3), total nitrogen (TKN), and total phosphorous (TP) transformations were tracked through the system processing. In the AD process, nutrients are transformed from organically bound to dissolved forms, which is better of plant uptake. Tracking the nutrients also helps generate data for the quantity of N and P that is present in the liquid manure and available as crop fertilizer.

The average TKN concentration for DAF and cranberry wastes over 13 months were 4,170 ±280 mg-N/L and 2,840 ±330 mg-N/L, respectively (Figure 7B). The average TKN for the DM before SS, the DM after SS, the DM digester influent, and digester effluent were 1,890 ±170 mg-N/L, 1,950 ±180 mg-N/L, 1,860 ±200 mg-N/L, and 4,030 ±260 mg-N/L, respectively.

The average TP concentration for DAF and cranberry wastes over 13 months were 870 ±130 mg-P/L and 500 ±70 mg-P/L, respectively (Figure 7C). The average TP for the DM before SS, the DM after SS, the DM digester influent, and digester effluent over 13 months were 300 ±40 mg-P/L, 300 ±40 mg-P/L, 450 ±90 mg-P/L, and 770 ±100 mg-P/L, respectively.

Ammonia (NH_3) content in the substrates over 13 months was highest in AD effluent (3,520 ±250 mg NH_3-N/L), followed by DM before SS (1,540 ±150 mg NH_3-N/L), DM influent (1,500 ±130 mg NH_3-N/L), DM after SS (1,420 ±140 mg NH_3-N/L), DAF (1,260 ±230 mg NH_3-N/L), and cranberry (690 ±190 mg NH_3-N/L) (Figure 7A).

Approximately 4,703 m^3 solids/year are separated from the liquid DM at Kilby Farm. After solids are separated from the liquid manure, the solids undergo composting, where the compost is turned twice per week to encourage aerobic microbial processes that generate usable N and P for crop application. The farm produced 4,245 metric tons of compost annually. When multiplied by the percentages of nutrients found in the compost (1.2% total N, 0.24% P, and 0.43% K), this equates to 50.9 metric tons of N, 10.1 metric tons of P, and 18.2 metric tons of K per year.

The nutrients traveling through the system are critical to the efficiency of the AD process as N and P are required for microbial growth and are a vital component of fertilizer. The concentration of the nutrients (TKN, TP) concentrations entering and leaving the system remain relatively equal between the influent and effluent, with increases in ammonium concentrations, as the organic material degrades releasing the dissolved form of nitrogen. It should be noted that the digester influent samples (each food processing waste and the liquid dairy manure) were tested separately, as they enter the digester through separate pumps. The digester effluent is one sampling point, which takes substrate from near the top of this periodically mixed digester. It is unknown if the mixing inside the digester is adequate to keep the DAF contents from rising the top of the digester and being more concentrated in the digester effluent. While multiple monthly samples were taken and tested in triplicate over a 13-month period, the inherent variability of co-digestion substrate digestion in the influent and effluent sampling should be acknowledged, especially when the samples have differing lipid content and thus differing stratification propensity.

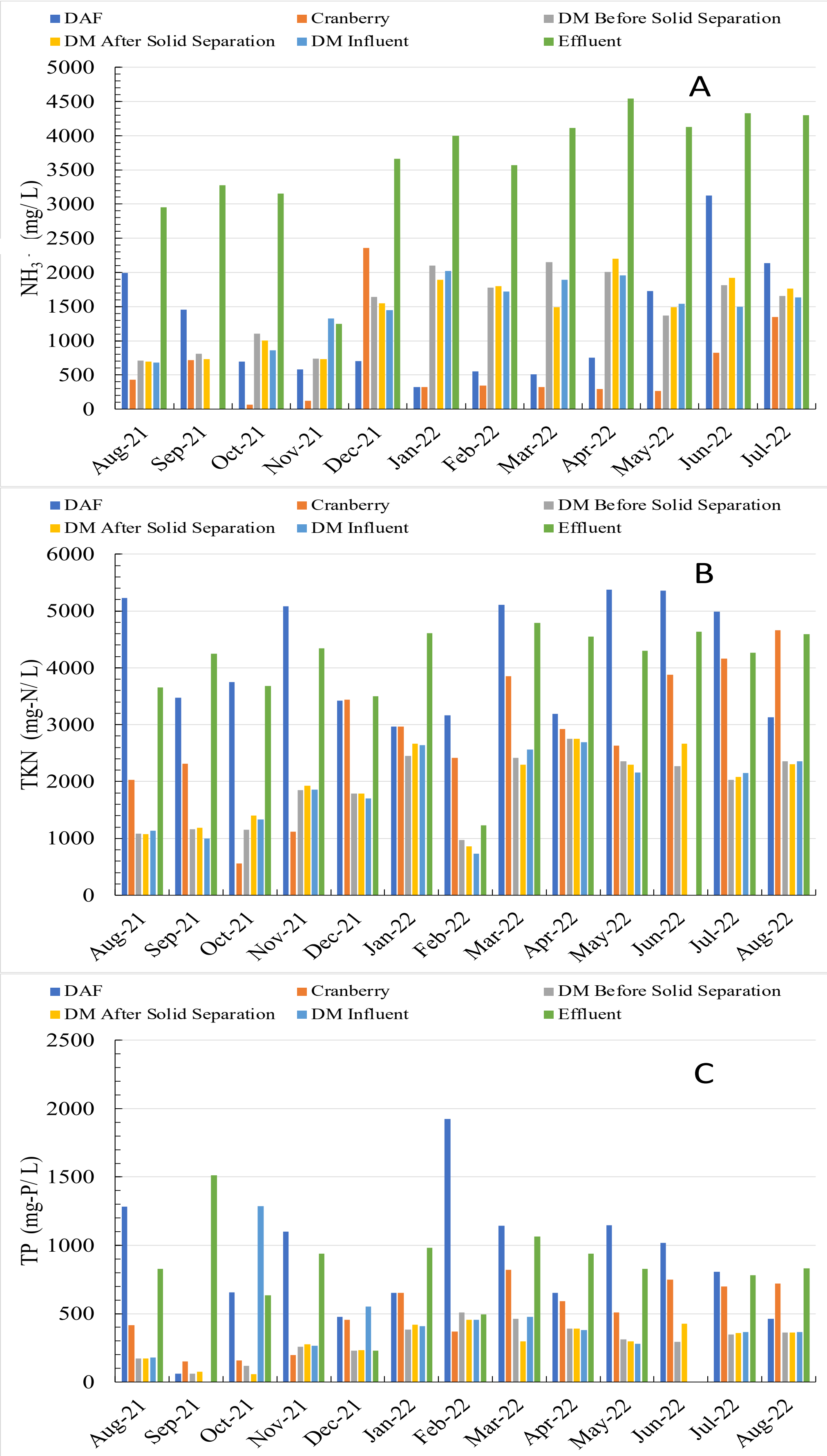

Figure 7: Average ammonia (NH_3) (A), total nitrogen (TKN) (B), and total phosphorous (TP) (C) concentrations for liquid samples over the sampling period.

4.5 Temperature and pH

The biological processes responsible for CH_4 production are affected by the digester temperature and temperature fluctuations. Anaerobic digesters are generally operated in the mesophilic (30-37 ºC) or thermophilic (50-60 ºC) range. Higher temperatures generally result in greater biological activity, and thus, biogas production, but can require more energy for heating compared to operating at lower temperatures. The results showed the system was operated in the higher end of the mesophilic temperature range (Figure 8). The average temperature throughout the monitoring period was 36.3 ºC, with a high of 38.7 ºC. This temperature provided adequate conditions for digestion and biogas production.

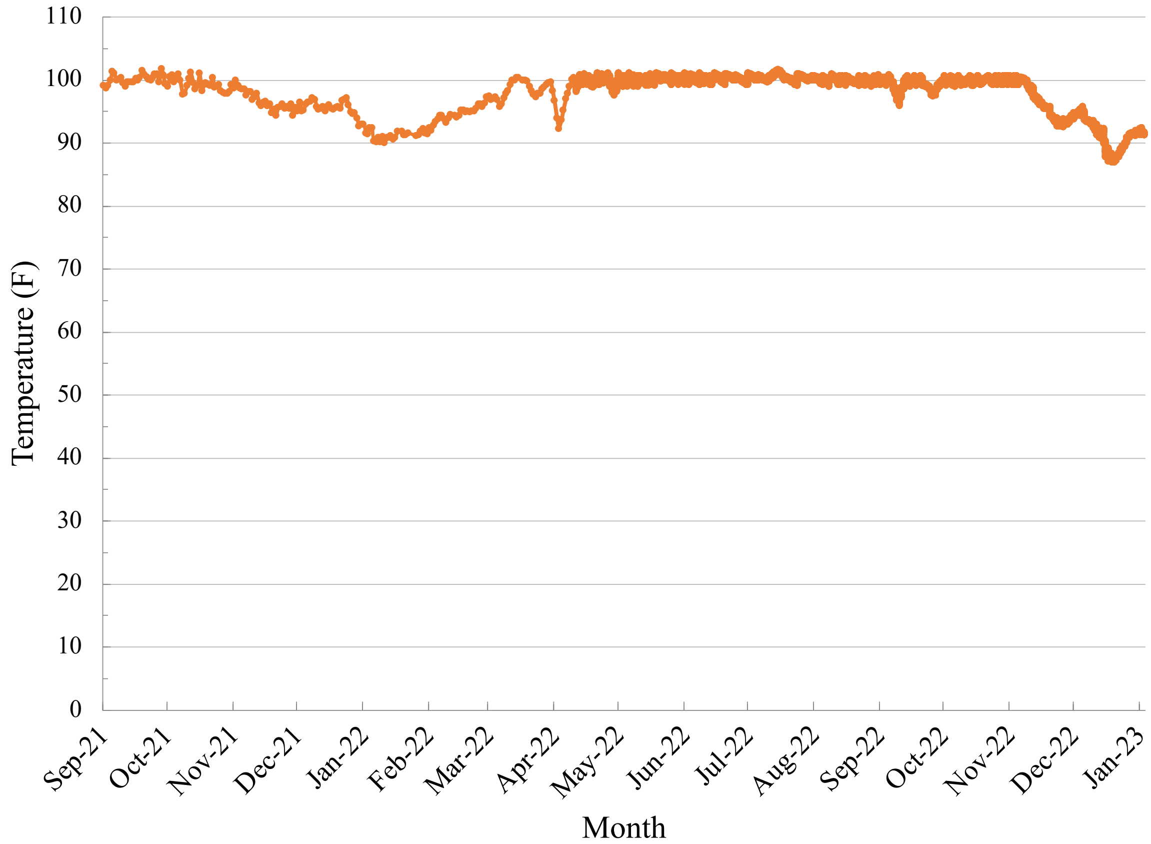

Figure 8: Temperature over the monitoring period for farm-scale AD system (°F).

The digestion process is also sensitive to pH, with the biological processes having a pH range of 6.5 to 8 for optimal CH_4 production[3]. High pH can indicate the buildup up of recalcitrant compounds, hindering the digestion process. Alternatively, low pH can indicate excessive acid buildup, leading to low biogas production, potentially killing methane producing microorganisms and reducing the efficiency of the AD process.

Throughout the monitoring period, the highest pH observed for DM influent was 8.2, while the lowest pH was observed in the cranberry influent (3.01) (Figure 9). Throughout the sampling period, cranberry had the lowest average pH (3.6 ± 0.1), the AD effluent had the highest average pH (7.90 ± 0.1), while the average pH of the combined feedstock influent (DAF, cranberry, DM influent) was 5.6 ± 0.1. The DAF waste had an average pH of 5.2 ± 0.1 and the DM liquid influent had an average pH of 7.8 ± 0.03 over the 13-month sampling period, with the higher pH of the DM influent helping to moderate the low pH of the food waste substrates.

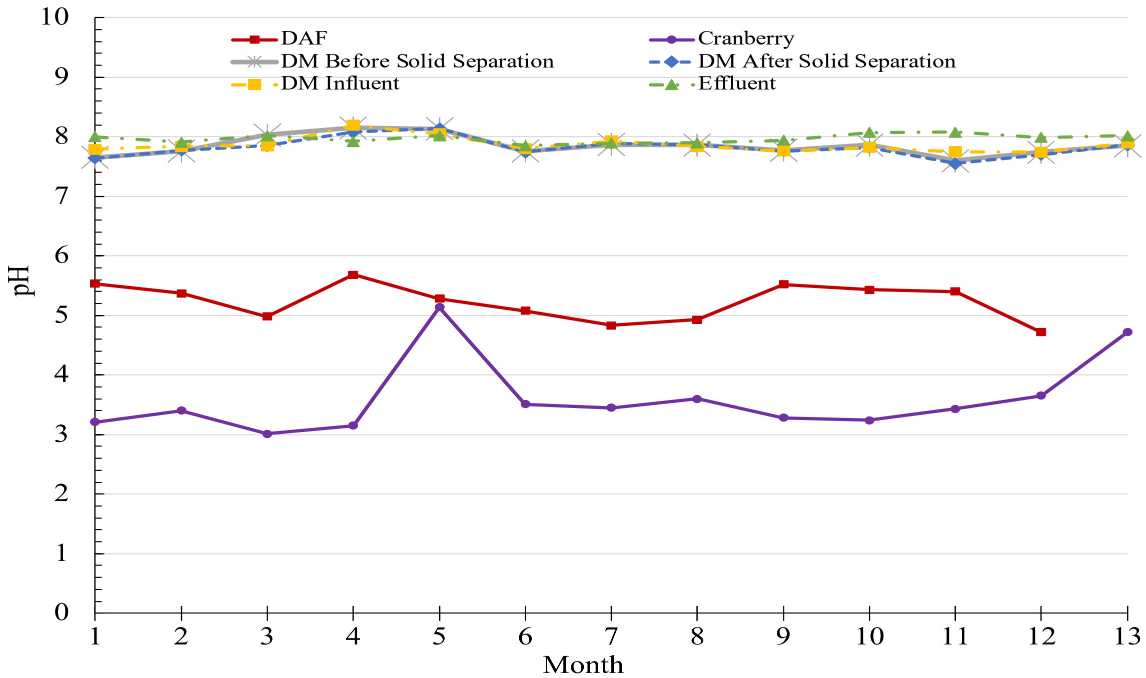

Figure 9: pH for liquid samples over the sampling period.

4.6 Volatile Fatty Acids (VFAs) Transformations

The digestion process involves three main processes: 1) hydrolytic bacteria use extracellular enzymes to convert complex organic material into soluble carbohydrates, fats, and proteins; 2) acid forming bacteria convert the soluble compounds into short-chained organic acids, known as volatile fatty acids (VFAs); and 3) methanogens use the VFAs to produce biogas[4,5]. The primary VFAs include acetic, propionic, butyric, and valeric acids (Figure 10). High VFA concentrations in the digester influent indicates that there is high biogas potential, while high VFA concentration in the AD effluent indicates lost CH_4 potential and low VFA concentrations in the AD effluent indicate that the digester is utilizing the available dissolved organic substrates.

The influent DM had the lowest average VFA concentration (693 ±115 mg/L). The DAF had the highest average VFA concentration (1,688 ±191 mg/L), followed closely by cranberry (1,526 ±273 mg/L). The AD effluent had an average total VFA concentration of 301 ±49 mg/L. Adding FW increases the amount of available substrate, in the form of VFAs, available for biogas production, with the majority of the VFAs (77%) used during digestion.

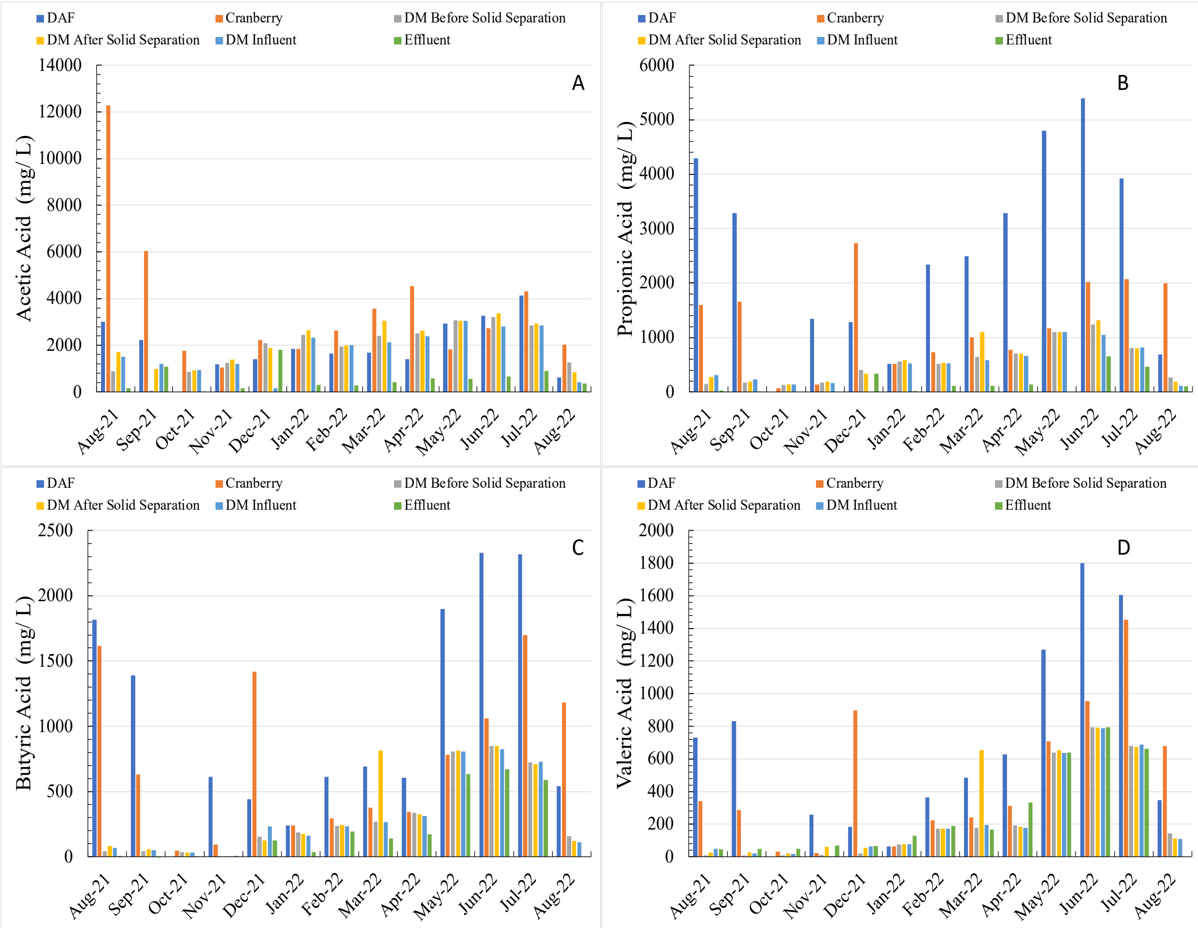

Figure 10: VFA concentrations (mg/L) of acetic acid (A), propionic acid (B), butyric acid (C), and valeric acid (D) over the sampling period.

4.7 Lab-Scale Biochemical Methane Potential (BMP) Testing

A biochemical methane potential (BMP) test was conducted with four individual substrates and two mixtures of DAF and cranberry co-digested with dairy manure and inoculum. Each sample was tested in triplicate. The inoculum for the BMP was from the Kilby Farm.

Table 1: Quantity of material loaded into the lab-based biochemical methane potential (BMP) reactors, including dissolved air flotation waste (DAF) from poultry processing, cranberry waste, dairy manure before and after solid separation (SS), and inoculum.

BMP	Sample Amount (g)	Inoculum (mL)
DAF	4.92	140
Cranberry	2.64	140
Dairy Manure after SS	51.56	140
Dairy Manure Before SS	53.76	140
DAF + Cranberry + Dairy Manure after SS	1.06; 0.42; 3.52	140
DAF + Cranberry + Dairy Manure before SS	1.06; 0.42; 3.52	140
Inoculum	0.00	140

The digestion vessels were 250 mL bottles with the total liquid volume shown in Table 1. Each bottle had a 140 mL of inoculum, with the amount of substrate added based on a 2:1 inoculum to substrate ratio based on VS. Prior to incubation, the BMP vessels were flushed with N_2 gas for three minutes to ensure anaerobic conditions. The vessels were then capped with a rubber septum and placed on a shaker at 130 rpm in a temperature-controlled incubator at 35°C. Biogas production was quantified volumetrically using a 50-mL glass, gas-tight syringe equilibrated to atmospheric pressure. The produced biogas was analyzed for CH_4 content by injecting 0.5 mL sample into an Agilent HP 7890A gas chromatograph. Biogas production and CH_4 content were measured daily during the first week of the experiment and approximately every other day the following week, with measurement frequency based on the quantity of biogas produced for the remainder of the 37-day experiment. The dairy manure, cranberry waste, poultry processing DAF waste and substrate mixtures were characterized for TS and VS (Table 2).

Table 2: Total solids (TS) and volatile solids (VS) given as concentration (g/kg) and percent (%) prior to digestion in biochemical methane potential (BMP) testing.

Sample	Solids Content TS (%)	TS (g/kg)	Organic Content VS (%)	VS (g/kg)
DAF	21.8 ± 0.7	218 ± 7	21.3 ± 0.6	212 ± 6
Cranberry	40.4 ± 0.2	404 ± 2	39.7 ± 0.2	397 ± 2
Dairy Manure before SS	2.67 ± 0.02	26.7 ± 0.2	1.95 ± 0.02	19.5 ± 0.2
Influent	2.83 ± 0.40	28.3 ± 4.0	2.03 ± 0.30	20.3 ± 3.0
Inoculum	21.8 ± 0.7	218 ± 7	21.3 ± 0.6	213 ± 6

4.7.1. Biochemical Methane Potential (BMP) Testing Results:

Total Solids (TS), Volatile Solids (VS), and pH:

The results showed decreases in TS and VS from the pre-BMP to the post-BMP (Table 3). In the DAF treatment, the pre-BMP TS was 2.58%, with a 36.0% decrease during digestion for a post-BMP of 1.65% TS. The sample with the largest decrease in TS during digestion was the cranberry waste, with a 37.04% decrease from 2.70% TS to 1.70% TS.

The DAF + Cranberry + Dairy Manure (DM) after SS had a 21.9% decrease in VS from pre-BMP to post-BMP. The DAF + Cranberry + Dairy Manure (DM) before SS had a 28.3% decrease in VS from pre-BMP to post-BMP. The DAF treatment had a 71.8% decrease in VS from 4.08% to 1.15% VS, the largest percent decrease across the samples (Table 3).

The digestion process is also sensitive to pH, with the biological processes having a pH range of 6.5 to 8 for optimal CH_4 production. The pH in the pre-BMP samples was from 7.68-8.05, and ranged from 7.55-7.85 in the post BMP samples, which was optimal pH range for CH_4 production.

Table 3: Total solids (TS) and volatile solids (VS) of the inoculum+ substrate mixtures in BMP reactors pre-BMP and post-BMP, given as percent of the total sample (%). Average values are taken from triplicate samples.

Sample #	Pre-BMP TS (%)	Post-BMP TS (%)	Pre-BMP VS (%)	Post-BMP VS (%)	Pre-BMP pH	Post-BMP pH
DAF	2.58 ± 0.03	1.65 ± 0.01	4.08 ± 2.10	1.15 ± 0.02	7.70 ± 0.06	7.66 ± 0.21
Cranberry	2.70 ± 0.06	1.70 ± 0.02	2.12 ± 0.03	1.17 ± 0.02	7.68 ± 0.03	7.85 ± 0.01
Dairy Manure after SS	2.17 ± 0.01	1.67 ± 0.09	1.55 ± 0.00	1.21 ± 0.02	8.01 ± 0.02	7.58 ± 0.02
Dairy Manure Before SS	2.49 ± 0.25	1.75 ± 0.01	1.59 ± 0.03	1.14 ± 0.02	7.98 ± 0.04	7.55 ± 0.00
DAF + Cranberry + Dairy Manure after SS	2.26 ± 0.01	1.76 ± 0.01	1.65 ± 0.03	1.18 ± 0.01	8.01 ± 0.06	7.76 ± 0.00
DAF + Cranberry + Dairy Manure before SS	2.31 ± 0.02	1.75 ± 0.04	1.69 ± 0.01	1.15 ± 0.04	7.96 ± 0.02	7.79 ± 0.02
Inoculum	2.25 ± 0.16	1.65 ± 0.00	1.49 ± 0.03	1.13 ± 0.00	8.05 ± 0.01	7.83 ± 0.04

4.7.2. Biogas and Methane Production

The CH_4 production from the mixtures were higher than the individual substrates when the CH4 production values were normalized by VS, which shows the efficiency of the digestion process. The DAF + Cranberry + DM before SS treatment had the highest CH_4 production (987 mL CH_4/g VS), which was a 39.4% increase in CH_4 production over DAF-only (708 mL CH_4/g VS). The DAF + Cranberry + DM after SS treatment CH_4 (958 mL CH_4/g VS) was lower than the DAF + Cranberry + DM before SS production, with a 35.3% increase in CH_4 biogas production compared to DAF-only (Figure 11; Table 4). Mixtures were more efficient in converting the organic matter to CH_4 than the individual substrates, likely due to the pH buffering capacity dairy manure combined with the VS-enriched food waste substrates.

Table 4: Average cumulative methane (CH_4) production (L CH_4/kg VS) for Kilby Farm laboratory-based biochemical methane potential (BMP) testing.

Mesophilic Digestion at 37 days (L CH_4/g VS)					
	Days of Digestion				
Substrate	**2**	**5**	**11**	**20**	**37-End**
DAF	25	326	661	685	708
Cranberry	0	0	98	609.7	696
Dairy Manure after SS	42	122	174	213	224
Dairy Manure Before SS	41	124	189	243	280
DAF + Cranberry + Dairy Manure After SS	162	741	839	906	958
DAF + Cranberry + Dairy Manure before SS	174	752	854	917	987

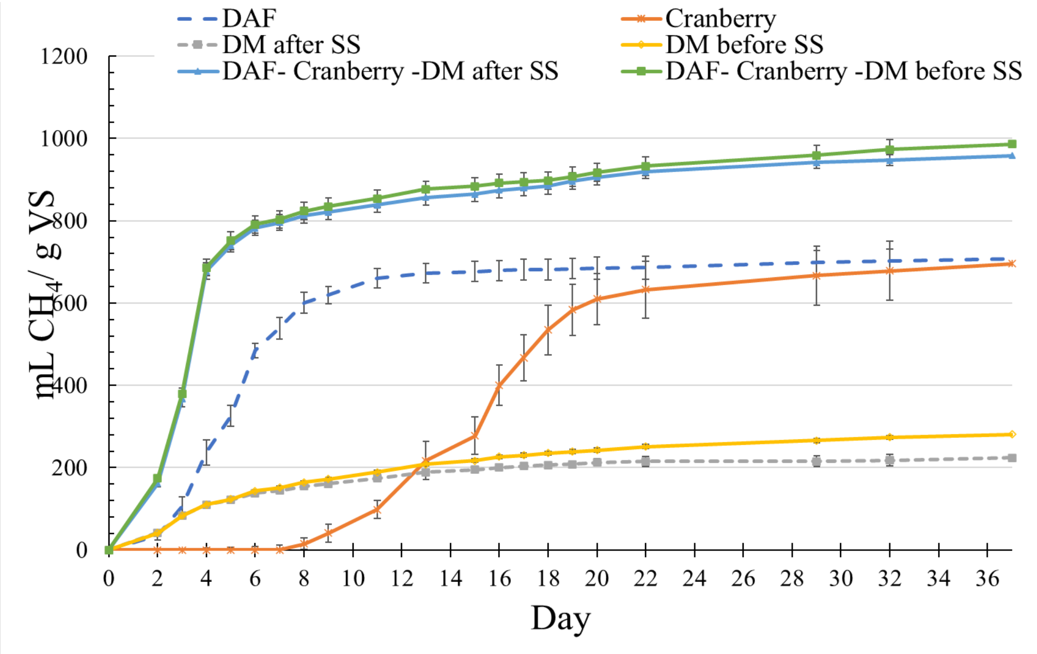

Figure 11: Cumulative methane (CH_4) production based on volatile solids (VS) for poultry processing dissolved air flotation (DAF) waste, cranberry waste, dairy manure (DM) before and after solid separation (SS), and mixtures of these substrates.

It should be noted that the total CH_4 production values (when the values were not normalized by VS) were higher in the individual treatments compared to mixtures (Figure 12). This means that while there is more bioenergy production potential with the individual substrates, the efficiency of the process decreases. When the production values were normalized by VS, the mixtures were more efficient than the individual substrates (Figure 11).

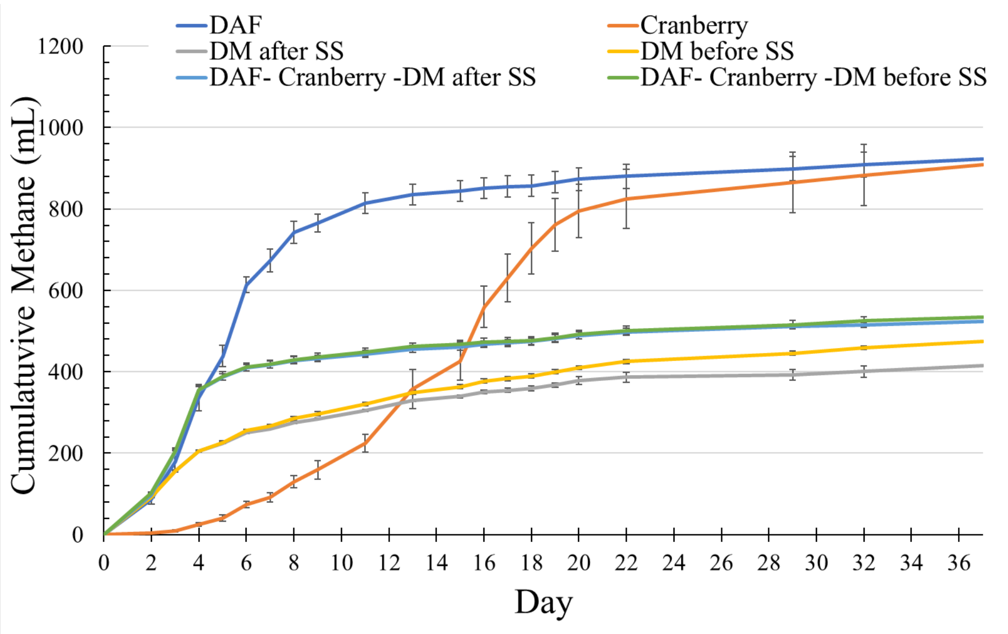

Figure 12: Cumulative methane (CH_4) production for poultry processing dissolved air flotation (DAF) waste, cranberry waste, dairy manure (DM) before and after solid separation (SS), and mixtures of these substrates.

Analyzing the monitoring data from Kilby Farm showed that the average cumulative CH_4 production efficiency was 631 L CH_4/kg VS. While the on-farm CH_4 production was 44% lower than the BMP, this was expected due to the different operational parameters between the farm-scale and lab-scale operation. In the lab-scale BMP, the temperature was and maintained at 35 °C, the mixture was agitated, and the digestion period was a 37-day batch process. At the Kilby Farm AD system, there are slight variations in temperature in the winter and summer. Additionally, the quality and exact quantity of materials entering the AD system at Kilby Farm digestion system can fluctuate.

4.8 Manure Injection and Surface Application

Kilby Farm utilizes manure injection and surface application of lagoon-stored liquids to add nitrogen for crop production. Occurring bi-annually, Kilby farm pumps the liquids out of the lagoon through a dragline for two separate methods of fertilizer application: 1) a disc-coulter style injection system splits the soil, injects the liquid manure, then covers the application zone with soil; 2) a manure spreader applies the liquid manure to the soil above ground via a high-pressure pump. Throughout this process, nitrogen can be released into the atmosphere. Liquid manure fertilizer has high concentrations of N in the form of ammonium (NH_4), as the liquid manure contacts the soil, bacteria utilize an enzyme (urease) to convert the NH_4 into NH_3, a volatile gaseous form of N. This process can occur rapidly when fertilizer is applied, however, manure injection typically reduces the amount of N lost as the fertilizer is covered with soil. To assess the quantity of NH_3 lost in the fertilizer application process at Kilby Farm, UMD conducted sampling to capture NH_3 volatilization from both application processes. Manure injection was shown to be a much more effective method of reducing NH_3 volatilization compared to surface application (Table 5). As a result, manure injection led to nearly 100% reduction in NH_3 volatilization. It should be noted that depending on the time of year, surface application may be the only fertilization option, as manure injection is used when the crops are not growing while side dressing surface application can occur while crops are being grown.

Table 5: Ammonia (NH_3) volatilization from surface application and manure injection.

Process	Sample Time	Average NH_3 Concentration (mg NH_3-N/L)
Surface Application	1 Hour	4.27
Surface Application	3 Hours	5.27
Surface Application	24 Hours	16.40
Manure Injection	1 Hour	Below detection limit
Manure Injection	3 Hours	Below detection limit
Manure Injection	24 Hours	Below detection limit

4.9 Life Cycle Assessment (LCA) of Kilby Farm:

This study performed an LCA used 12 months of data sampling, material inputs, and processing conditions were incorporated into the LCA to investigate the inputs and outputs of the farm-scale anaerobic co-digestion and composting processes. The impact categories analyzed were: 1) Eutrophication, 2) Global Warming (GHG), 3) Acidification, 4) Ozone Depletion, 5) Fossil Fuel depletion, 6) Carcinogens, 7) Non-carcinogens, 8) Respiratory Effects, 9), Ecotoxicity, and 10) Smog. The LCA explored the impacts on the environment, GHG emissions, and human health impacts from five scenarios (**Error! Reference source not found.**6).

Table 6: The life cycle assessment (LCA) scenarios based on the functional unit of 1 year and 1 ton of organic waste. The scenarios included anaerobic digestion (AD) of food waste (FW), dairy manure (DM) and composting of solids separated from DM.

Scenario	**Description of Scenario**
No AD, no DM solids composting **(Baseline)**	No AD system, all dairy manure stored in an open lagoon, and no DM solids separation or composting.
AD of FW, DM, DM solids composting **(Current Conditions)**	AD of liquid DM and FW, with DM solids composting, CHP energy production from biogas.
AD of FW, all DM, without DM solids composting **(Scenario A)**	AD of FW and DM, no DM solids separation and composting.
AD of DM, with DM solids composted **(Scenario B)**	AD of DM with no FW co-digestion and the DM solids separated and composted.
AD of DM, no DM solids composting **(Scenario C)**	AD of all DM with no FW co-digestion and no DM solids separation and composting.

The baseline scenario analyzed no AD or solids composting, where all manure was stored in an open lagoon to analyze the impacts of manure storage and infrastructure without mitigating technologies, such as biogas capture or compost product. The baseline scenario considered the GHG emissions that would potentially be emitted from anaerobic conditions in an uncovered lagoon storing all the DM manure produced on-farm. Currently, Kilby Farm co-digests liquid dairy manure with food processing waste and the dairy manure solids are used for composting (current conditions). The current conditions explored the system as it is operated on Kilby Farm. Scenario A had co-digestion of all dairy manure and food processing waste without dairy manure solids composting, with all manure produced on-farm digested. Scenario B investigated mono-digestion of liquid dairy manure with dairy manure solids composted, excluding the transportation, infrastructure, and incorporation of FW into the system. Biogas reductions and energy generation decrease (82.5%) associated with mono-digestion of DM were included based on data from our biochemical methane potential (BMP) of the wastes obtained from the farm-scale AD system (Section 4.7). Scenario C examined mono-digestion of all dairy manure and no solids composting.

Two LCA analyses were performed for all scenarios using two functional units. The first LCA functional unit was one year (365 days), with the project inputs, outputs, and environmental impacts based on material input and outputs over one year of operation. The second LCA functional unit was one ton of organic waste, with inputs, outputs, and environmental impacts based on material input. All scenarios with AD included the electricity consumption for the AD system, such as feeding pumps, and mixing pumps. Based on data obtained from the farm-scale AD system, all scenarios with compost generated a value-added product of 3,822 m^3 based on an initial estimate of solids produced per year and assuming all separated DM solids (~27%) were composted.

Annually, the farm-scale AD system processed 17,362 m^3/yr of liquid DM (~73% of DM waste stream) and received 8,290 m^3/yr of FW. The solid separation unit separated 4,703 tons/yr (~27% of DM waste stream) of solid DM. The average BTU for biogas with 60-80% CH_4 is 600-800 BTU. Based on 600 BTU, the yearly biogas production (1,831,450 m^3/yr) equated to roughly $3.8*10^{10}$ BTUs generated over the year. The biogas used in the CHP (1,322,306 $m^{3/}$yr) for energy generation was equal to $2.8*10^{10}$ BTU, while flared biogas (509,143 m^3/yr) equated to $1.07*10^{10}$ BTUs not utilized. As 72.2% of the produced biogas was combusted for energy production, the net energy balance was positive, with the heat from the CHP used for heating.

The baseline scenario (no AD, no DM solids compost) had the following impacts: global warming (23,751 T CO_2 eq/year), eutrophication (19 T N eq/yr), acidification (75 T SO_2 eq/yr), and ecotoxicity (62 CTUe x1,000,000/yr) (Table 10). The CO_2 emission of the baseline scenario totaled 23,751 T CO_2 eq/yr, where constructing the DM storage lagoon (6,024 T CO_2 eq/yr) and environmental emissions of DM from the lagoon (17,727 T CO_2 eq/yr) were the largest contributors to CO_2 emissions (Table 7, Figure 13).

Table 7: Impact quantities for all scenarios with the functional unit of one year.

Impact Categories	Unit	Baseline Scenario	Current Conditions	Scenarios		
				A	B	C
Global Warming	T $CO_{2\ eq}$/yr	23,751	4,495	4,506	4,284	4,296
Eutrophication	T N_{eq}/yr	19	-65	-64	-58	-57
Smog	T $O_{3\ eq}$/yr	480	380	364	324	307
Acidification	T SO_2 eq/yr	75	-166	-166	-151	-151
Carcinogens	CTUh/yr	1.55	0.89	0.9	0.91	0.92
Non-carcinogens	CTUh/yr	2.5	0.38	0.6	-0.71	-0.49
Respiratory Effects	kg $PM_{2.5\ eq}$/yr	9	0.74	0.71	0.82	0.79
Ecotoxicity	CTUe X 1,000,000	62	-154	-149	-137	-132
Fossil Fuel Depletion	MJ Surplus/yr	5,134,437	5,268,569	5,325,492	4,738,453	4,795,376
Ozone Depletion	kg CFC-11 eq/yr	0.54	0.57	0.56	0.51	0.5

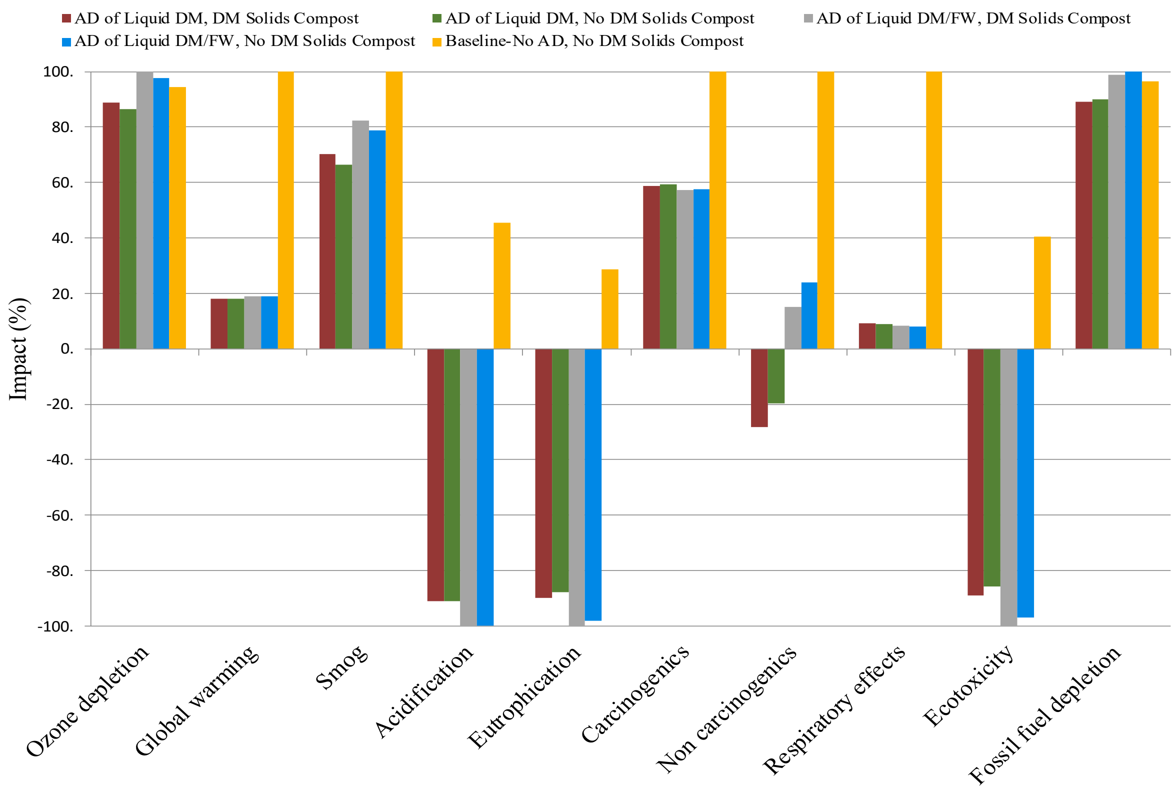

Figure 13: Environmental impacts for life cycle assessment (LCA) of five scenarios for farm-scale anaerobic digestion (AD) of dairy manure (DM), food waste (FW) and composting of dairy manure solids with a functional unit of one year.

The current conditions displayed less emissions in global warming (4,495 T CO_2 eq/year), smog (380 T O_3 eq/yr), acidification (-166 T SO_2 eq/yr), eutrophication (-65 T N eq/yr), ecotoxicity (-154 CTUe x1,000,000), respiratory effects (0.74 kgPM 2.5 eq/yr), non-carcinogenics (0.38 CTUh/yr), and carcinogenics (0.88 CTUh/yr). When comparing the current conditions to the baseline scenario, there were large reductions in almost all assessment categories: acidification (320%), eutrophication (447%), ecotoxicity (348%), respiratory effects (92%), global warming (81%), non-carcinogenics (85%), carcinogenics (43%), and smog (18%) (Figure 15). Global warming reductions were nearly equivalent for all other scenarios at >81% reductions compared to the baseline scenario. However, the current condition increased fossil fuel depletion (3%) and ozone depletion (6%) more than the baseline scenario due to the transport of FW.

Compared to the current conditions, Scenario C (DM mono-digestion, no DM solids separation and composting) had the largest reductions in ozone depletion (8%) and smog (33%), while Scenario B (DM mono-digestion, DM solids composting) had the largest reduction in fossil fuel depletion (8%). These reductions were attributed to excluding FW transport and composting, as FW transport, the construction of the FW containers, diesel used for compost agitation, and concrete used for composting pads increased fossil fuel use, ozone depletion, and smog. To more efficiently investigate GHG emissions and nutrient flow, separate analyses were conducted for global warming and eutrophication process contributions to quantify emissions from each scenario.

Global warming is one of the most important categories due to the GHG potential and climate impact of CO_2 emissions. LCA data indicated that incorporating AD, in any configuration, drastically reduced global warming (>81%) compared to the baseline scenario (Figure 14). Compared to the baseline scenario, large reductions (>81%) in CO_2 emissions were observed in the current conditions (4,495 T CO_2 eq/yr), Scenario A (4,506 T CO_2 eq/yr), Scenario B (4,284 T CO_2 eq/yr), and Scenario C (4,296 T CO_2 eq/yr). When the digester was added, the avoided CO_2 emissions from electricity production in AD of FW and DM (2,242 T CO_2 eq/year) substantially offset the emitted CO_2 from the AD cover (6.7 T CO_2 eq/yr), pump electricity consumption (5.8 T CO_2 eq/yr), concrete (442 T CO_2 eq/yr), and pump construction (175 T CO_2 eq/yr). This resulted in a net 1,612 T CO_2 eq/yr in avoided emissions.

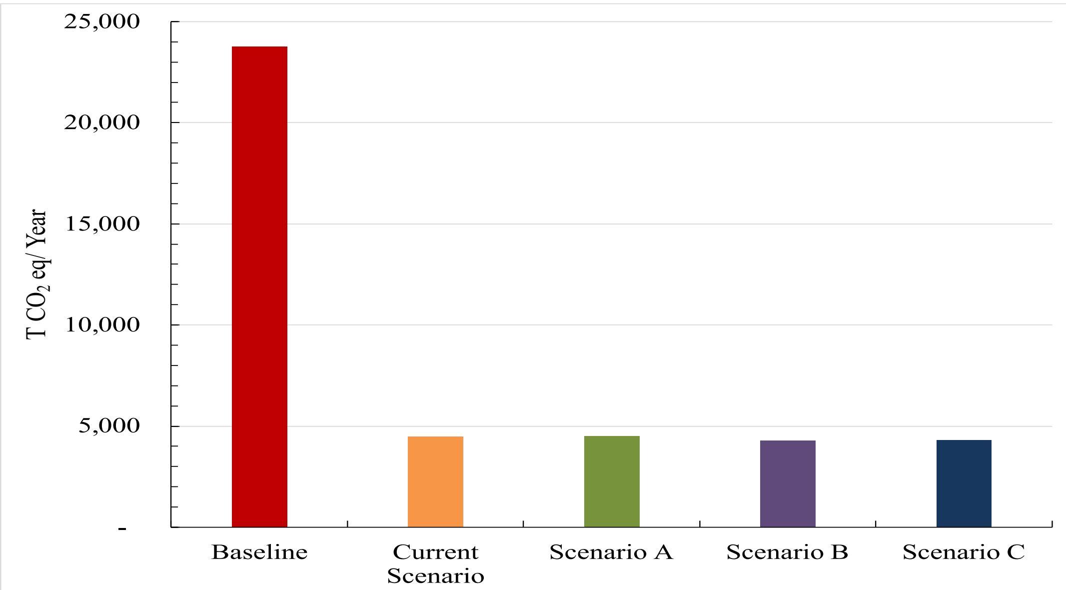

Figure 14: Global warming impacts from all LCA scenarios (T CO_2 eq/year).

Food waste (FW) heavily impacted global warming in the scenarios and the current conditions. The transportation in ton-kilometers (tkm) and concrete for the FW storage pits contributed to the more than 15% of the overall emissions (682 T CO_2 eq/yr). This impact was completely offset by the increased electricity production from DM and FW co-digestion (2,242 T CO_2 eq/yr), yielding a net CO_2 decrease of 1,560 T CO_2 eq/yr (30% decrease). The AD of DM without FW in Scenarios B and C led to decreases in biogas and electricity production (1,769 T CO_2 eq/yr). This was shown in the LCA as less reductions in CO_2 emissions and global warming impacts, as the energy generation was less effective at offsetting the impacts of the AD lagoon (6,024 T CO_2 eq/yr). Nonetheless, the similarity in global warming impact reduction for all scenarios compared to the baseline shows that FW digestion or dairy manure mono-digestion are beneficial, with a substantial increased renewable electricity production with FW inclusion.

In the current conditions, the reduction in CO_2 emissions of compost production (611 T CO_2 eq/yr) was nearly eliminated by the global warming impact of the material and energy inputs from compost operation and facility construction (concrete: 571 T CO_2 eq/year, diesel: 25 T CO_2 eq/yr, and wood: 2.5 T CO_2 eq/yr). Consequently, compost had a minor net reduction in global warming (11 T CO_2 eq/yr). Despite the loss of energy generation from excluding FW, Scenario B was most effective at decreasing CO_2 emissions due to the small benefit of compost (1% reduction in T N eq/yr).

Compared to the baseline scenario, large N reductions were observed in the current conditions (448%), Scenario A (436% reduction), Scenario B (405% reduction), and Scenario C (400% reduction) (Figure 15). Integrating FW in AD exhibited larger reductions in N emissions compared to AD of DM alone in Scenarios B and C. The electricity generation from co-digestion (current condition and Scenario A) decreased N emissions by 82.5% (10.2 T N eq/year) compared to Scenarios B and C (1.78 T N eq/year). Eliminating composting (1.19 T N eq/year) in Scenario A removed 1 ton less N compared to the current conditions. Reducing renewable energy generation by 82.5% and eliminating compost in Scenario C increased N emissions by nearly 10 T. These data indicate that the current conditions at Kilby Farm is the most sustainable approach to eutrophication reduction.

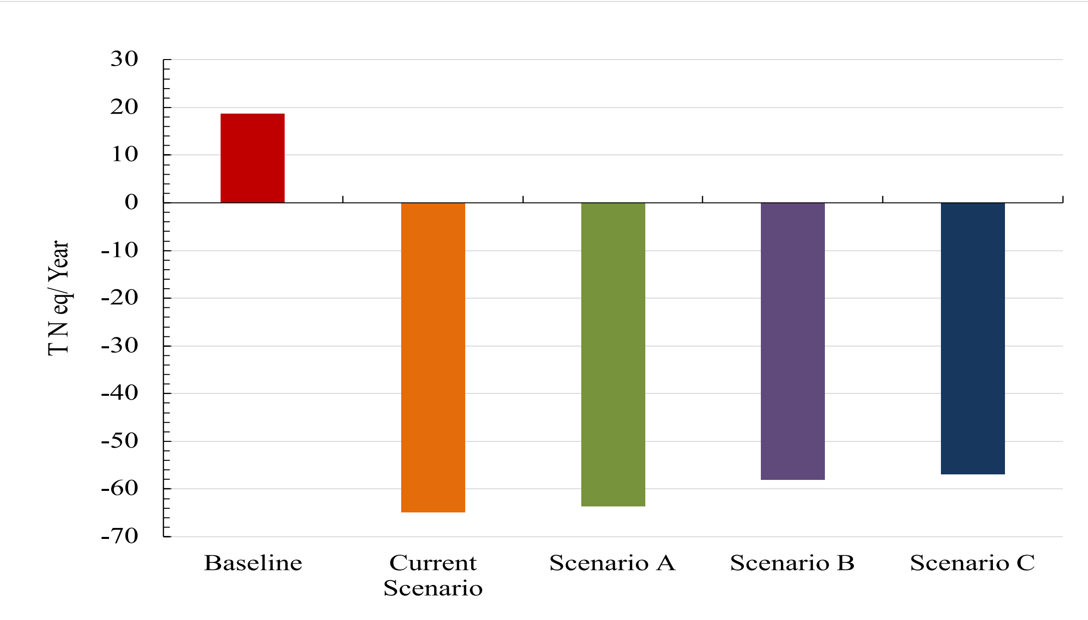

Figure 15: Eutrophication impacts from all LCA Scenarios (T N eq/year).

Overall, the LCA results showed that co-digesting FW and AD using the current conditions at Kilby Farm led to the greatest reductions in acidification, eutrophication, ecotoxicity, and carcinogens due to increased biomass valorization and greenhouse gas emission captured that would have been emitted in an open-air manure storage lagoon. Scenarios B and C were more advantageous in fossil fuel depletion, smog, global warming, non-carcinogens, and ozone attributed to excluding composting and FW inclusion. The LCA suggested that increased electricity from co-digestion resulted in a positive net energy gain while yielding the least environmental impacts. Moreover, compost had a lesser impact in reducing impacts than digestion, though composting still generating a decrease in global warming and eutrophication impacts. From this study, the LCA results indicate that CHP is a sustainable approach to energy generation from farm-scale AD due to efficient energy production, although reducing FW transport distances would yield greater emission mitigation.

5. Study Results Summary

The AD system processed 17,362 m^3/yr of liquid DM (~74% of DM waste stream) and received 8,290 m^3/yr of FW, producing 5,017 m^3 biogas/day (1,831,450 m^3 biogas/yr based on monitoring data) with an average digester conversion efficiency of 631 L CH_4/kg VS. This means that a large portion of the FW and DM entering the system is converted to CH_4-rich biogas. While biogas can be combusted to generate electricity and capture heat, high concentrations of hydrogen sulfide (H_2S) can be corrosive to the electric generator. The H_2S scrubbing system reduced almost 100% of H_2S produced. The majority of produced biogas was consumed in the CHP (72.2%, 1,322,306 m^3/yr) to produce 1,983,722 kWh/yr of electricity, with 27.8% of the biogas (509,134 m^3/yr) used in the flare and not producing renewable energy, as the generator was mainly run at capacity. The electricity production at Kilby Farm produced enough kWh to power 190 homes for one year. Additionally, the residual heat of the combine heat and power (CHP) generator was used to heat the digester and keep it at 36.3 ºC (97 ºF) eliminating the need for additional heat input to keep the digester at the mesophilic temperatures optimal for bioenergy production. The solid separation unit processed 4,703 m^3/yr of solid DM that generated compost as a value-added product.

When analyzed through an LCA perspective, dairy manure co-digested with food processing waste drastically reduced global warming (>81%) compared to the baseline scenario of an open-air manure lagoon and no digestion or composting. It was shown that transportation of the food processing waste and construction materials needed for composting (e.g., fuel for composting turning and concrete pad installed) had the largest contribution in GHG emissions (682 T CO_2 eq/yr) and eutrophication (1.19 T N eq/yr) due to the long distances needed to transport the DAF (50 km) and cranberry (167 km) and the fuel and materials needed for compost production. However, these GHG emissions were offset by the substantial energy production from the electricity generation when co-digesting FW and DM, resulting in an overall net CO_2 reduction of 20,000 tons of CO_2 every year. With the current configuration, the Kilby Farm digester offsets the GHG emissions emitted by 4,000 cars every year. The LCA showed that lowering the transportation distances for FW and increasing the compost output would further reduce environmental impacts (Figure 16).

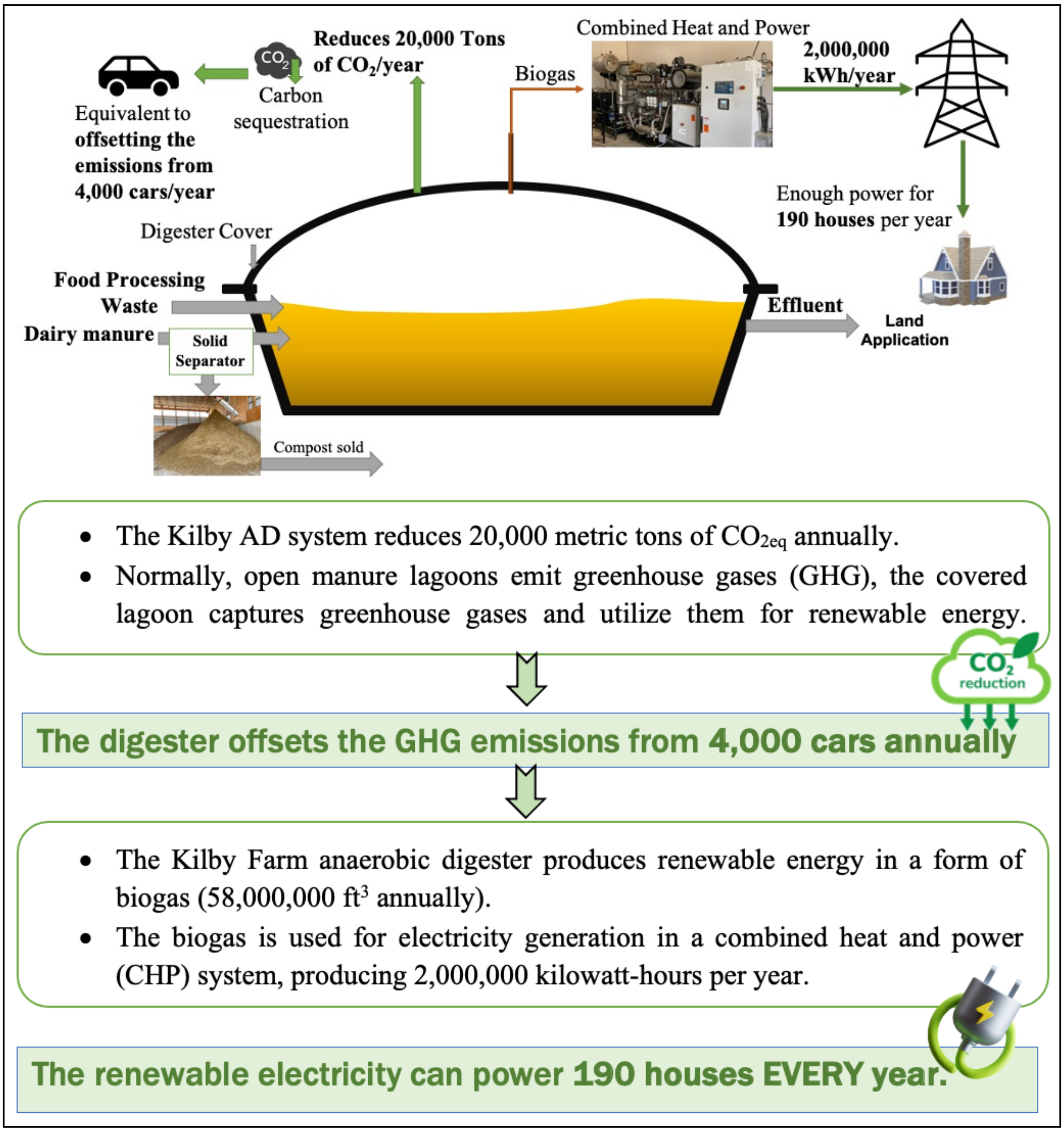

Figure 16: Overview of the Kilby Farm digester greenhouse gas (GHG) annual emission reductions.

6. Lessons Learned

- The life cycle assessment (LCA) found that the current conditions at Kilby Farm was the most effective in mitigating emissions in 8 out of 10 impact categories.
- Using the biogas in the CHP generated a net positive energy production, producing nearly 2,000,000 kWh/year.
- Implementing the hydrogen sulfide (H_2S) scrubbing system was near 100% efficiency for the entirety of the monitoring period.
- The laboratory biochemical methane potential (BMP) analysis showed that co-digesting DAF, cranberry, and liquid DM was more efficient in turning organics to bioenergy. Higher biogas production is seen with only digesting FW, but co-digesting with DM allowed for a more optimal pH conditions and a more efficient process.

7. Conclusions

A farm-scale anaerobic digestion and nutrient capture system was monitored and analyzed for its energy production and impact on increasing the sustainability of DM and FW disposal in Maryland. Over 13 months, University of Maryland personnel collected monthly samples from nine sampling points to verify the system performance. The results showed that using anaerobic digestion to convert DM and FW to biogas and fertilizer is possible in Maryland. Based on the monitoring results, 17,362 m^3/year of liquid DM and 8,290 m^3/year of FW were added to the system, with an average CH_4 efficiency of 631 L CH_4/kg VS during the 2021-2023 monitoring period. The compost system produced approximately 4,245 metric tons of compost per year , which could be sold for profit. In addition, the liquid effluent was used as fertilizer for crop application, with elimination of ammonia emissions when manure injection was used.

The LCA analysis shows the current operations at Kilby Farm was the most sustainable scenario with the largest reductions in 8 out of the 10 impact categories. A baseline scenario (no AD system and no composting) and three alternative scenarios (no composting or DM mono-digestion) were compared and analyzed for GHG emissions and eutrophication potential. The LCA showed that the baseline scenario emitted nearly 25,000 T CO_2 eq/yr, and 19 T N eq/yr. Comparatively, the current scenario at Kilby Farm reduces the GHG emissions by over 81% (4,495 T CO_2 eq/yr), and eutrophication by 448%. While Scenarios B and C yielded greater reductions in ozone depletion and fossil fuel depletion, the added electricity production from co-digestion of FW and DM in the current scenario greatly exceeded the expenditure of fuel and materials for FW transportation and storage. Overall, the current system at Kilby Farm proved to be the most efficient and least environmentally harmful scenario, however, increasing the compost output and reducing transportation distances for the FW would yield additional environmental reductions.

8. References

[1] American Public Health Association (APHA) *Standard Methods for the Examination of Water and Wastewater, 21st ed.; APHA:Washington, DC, USA, 2005.*; 2005; ISBN 0875532357.

[2] Jirka, A.M.; Carter, M.J. Micro semiautomated analysis of surface and waste waters for chemical oxygen demand. *Anal. Chem.* 1975, *47*, 1397–1402.

[3] Shelford, T.; Gooch, C.; Choudhury, A.; Lansing, S. *A Technical Reference Guide for Dairy-Derived Biogas Production, Treatment, and Utilization*; 2019;

[4] Eryildiz, B.; Lukitawesa; Taherzadeh, M.J. Effect of pH, substrate loading, oxygen, and methanogens inhibitors on volatile fatty acid (VFA) production from citrus waste by anaerobic digestion. *Bioresour. Technol.* 2020, doi:10.1016/j.biortech.2020.122800.

[5] Wainaina, S.; Lukitawesa; Kumar Awasthi, M.; Taherzadeh, M.J. Bioengineering of anaerobic digestion for volatile fatty acids, hydrogen or methane production: A critical review. *Bioengineered* 2019.