APPLICATION FOR COMPONENT ADDITION TO NRCS

NRCS Practice Standard 317 (Evaluation Followed Process Standard 629 Protocol)

For Acceptance of Compost Aeration

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APPLICATION FOR COMPONENT ADDITION TO NRCS Practice Standard 317 (Evaluation Followed Process Standard 629 Protocol):

Compost Aeration

REQUEST

Natural Resources Conservation Service (NRCS) Conservation Practice Standard Composting Facility (Code 317) "…is a standard for a facility that will accommodate and facilitate a desired composting process."

NRCS Practice Standard 629 Waste Treatment (CPS 629) is a broad standard for waste treatment which establishes a standard format for presenting the information related to evaluating manure treatment technologies. Newtrient has developed a testing and reporting protocol for manure treatment technologies based on CPS 629 that was used to evaluate aerated composting and heat recovery technology vs traditional turned windrow composting at Vermont Natural Ag Products, Inc. (VNAP), a subsidiary of the Foster Brothers Farm, Inc. in Middlebury, Vermont. This application is for inclusion of a supplement to code 317 under "*Compost Aeration*".

BRIEF DESCRIPTION OF COMPONENT CLASS

Aerated Compost, also known as Aerated Static Pile Composting (ASP Compost) or Forced Air Compost, is an aerobic thermophilic composting process managed by incorporating positive (pushing air) and negative (pulling air) forced aeration to accelerate the composting process for manure, bedding, forest residuals, food scraps and other biomass.

By delivering air through perforated pipes at the bottom of the pile, the pile stays oxygenated creating the best possible conditions for heat-loving microorganisms including bacteria, actinomycetes, and fungi to multiply and break down large quantities of organic matter over a relatively short period of time. Not only does the air flow maintain the population and diversity of the microbes within the pile but it also reduces foul odors that could occur if parts of the pile become anaerobic.

DETAILED DESCRIPTION

While specific technical approaches within the larger class have notable distinction, the technology is applied in the following systems approach, which also captures thermal energy via a heat recovery system, as described in **Figure 1**.

Compost windrows are placed on a hard surface containing a shallow trench oriented longitudinally with the windrow. The trench contains perforated high-density polyethylene (HDPE) piping bedded in wood chips. These pipes are connected to solid, insulated HDPE piping which runs to a shipping container outfitted with circulation fans and a heat exchanger. While the circulation fans are negatively aerating (i.e., pulling vapor from) the compost, warm vapor entering the system transfers heat energy to water piped through the heat exchanger.

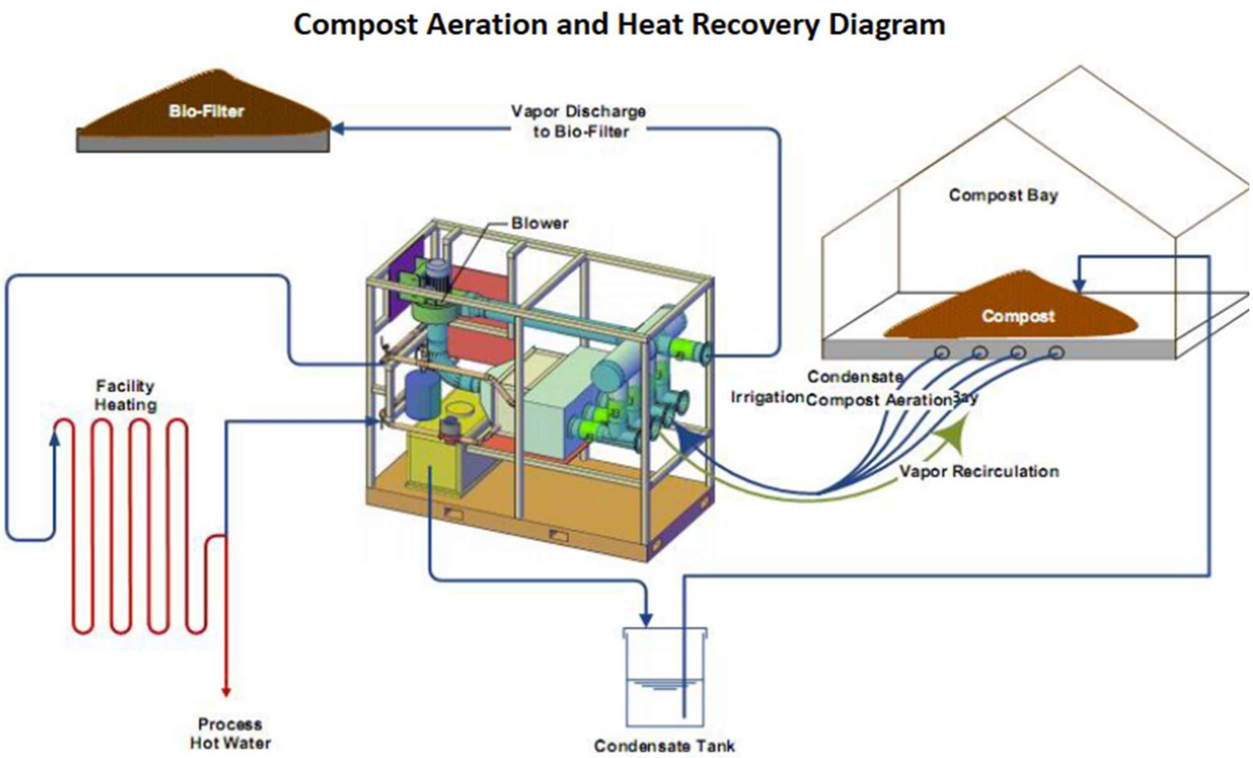

Figure 1. Compost aeration and heat recovery diagram.

This system is set up with four zones of perforated piping. At any given time, one of three scenarios is typically taking place.

1. Vapor is pulled from one zone, run through the heat exchanger, and exhausted to the environment;
2. Fresh air is pulled from the environment and used to positively aerate one zone; or
3. Vapor is pulled from one zone, run through the heat exchanger, and pushed into another zone.

Specific to a general compost aeration system, the following technical steps are at the core of processing and common to all technical versions commercially available. First, a high-volume blower is used to periodically deliver ambient air into the core of the compost pile. A typical cycle is 2- to 3-minutes on followed by 20- to 30-minutes off, giving the operator the ability to maintain aerobic conditions within the pile, mitigate odors and greatly accelerate the rate of composting. This allows for control of the temperature within the pile because as airflow increases, the heat in the core of the pile is displaced and temperature decreases. The temperature within the pile must be maintained between 130°F and 150°F. In the most basic terms, a compost aeration system includes the following five components:

- a *blower* which is typically connected to a timer or a temperature sensor triggering the blower fan
- a *manifold* that delivers the air, often with PVC pipe or other piping materials outfitted with perforations or holes to allow uniform distribution of air into the bottom of the pile
- a *Plenum Layer,* which is the bottom layer of the pile, usually comprised of wood chips to distribute air flow evenly across the pile and drain and absorb excess moisture away from the compost mix
- a *Compost Pile*, with a Carbon to Nitrogen (C:N) nutrient balance around 20-40:1, bulk density around 550-950 pounds per cubic yard and moisture content of 50 to 60 percent with pile height around 8 to 10 feet
- a *Biofilter* layer that serves as an essential component cover to insulate the pile, reduce odors, retain nutrients within the pile, provide a barrier to vectors, shed rainfall and retain moisture

HOW PROPOSED SYSTEM ACCOMPLISHES PURPOSES OF THE STANDARD

As organic waste streams become increasingly abundant with increases in human population and livestock rearing, so increases the need for efficient management of these wastes. Organic wastes such as manure, biomass, food scraps, and straw, among others, hold immense value as compost feedstocks. Compost is a valuable soil additive for agricultural producers and homeowners alike, but compost generation, the process used to transform waste into a soil amendment, is a time and space-intensive process and not without challenges.

To address these challenges, innovative composting technologies continue to emerge and crowd into the market with the potential to create new revenue streams and reduce greenhouse gas emissions and water quality as well as reduce time and space requirements for compost producers. However, adopting a new technology can be intimidating and nuanced and often presents financial and operational risks; therefore, third-party evaluation is a necessary tool to help producers manage risk and make informed decisions.

Newtrient (www.newtrient.com), a dairy industry-sponsored company focused on value-added and environmentally beneficial management of manure, has recently completed a review of technology classes within manure management and their impact on key critical environmental indicators. One such review, complete with quantitative analysis, summary discussion, and peer-reviewed literature citation is for Composting and is attached in Appendix A of this application. In summation and building upon that Appendix is the following brief discussion of key water, air, and other environmental indicators that are impacted by this class of technology and applicable to the purposes of Standard 317. Appendix B uses data from one commercial installation to offer both a visual and nutrient profile to show the impact that inclusion of a Compost Aeration system can have on an overall manure management system. Appendix C is the final report for the study conducted by the University of Vermont on the commercial installation.

Reducing nutrient content, organic strength

Composting is a stabilization process which can lead to nutrient losses that can both negatively affect the environment and render the compost less plant available; therefore, the balance of the carbon- and nitrogen-containing material in the pile is vital. During composting, complex chemical transformations are taking place within the pile to create a fully mature or finished compost.

According to Yang et al. (2019), aerated compost when compared with three other compost methods, significantly reduces N losses via leachates. The cumulative N losses through leachate were the lowest for aerated compost and accounted for only 0.38% of the initial total nitrogen (TN). Additionally, the data from the commercial installation comparison study (Appendix C) largely suggest that the aerated compost was more effective than a conventional windrow compost in preserving the sum of nitrate-nitrogen and nitrite-nitrogen (NOx-N) during the composting process, thereby likely curtailing undesirable nitrogen (N) losses via nitrate (NO_3)- leaching and gaseous emissions (including emissions of nitrous oxide (N_2O)). These observations suggest that compost aeration is a desirable composting method for efficient N management.

Phosphorous (P) loss through runoff or leachate is the biggest concern during aerated composting. Data show that aerated compost treatment provides better protection against P loss, possibly through immobilization by microbial communities and more stable redox-sensitive iron-phosphorus (Fe-P) due to more prominent aerobic conditions. Additionally, there is a lower risk for P loss through leaching from aerated compost, as water extractable phosphorus (WEP) concentrations were consistently higher in the conventional windrow compost. Though the windrow compost resulted in a slightly higher percentage of total P and WEP, the aerated compost was less prone to P leaching losses, indicating surface water and groundwater quality benefits from compost aeration systems (Appendix C).

Reducing odor and gaseous emissions

Compost aeration systems are designed to move air through the composting matter to promote the decomposition of material. During static aeration the pile does not require turning, reducing odor release through emissions of volatile carbon and sulfur compounds that occurs during the turning process. If odor becomes an issue, an aeration fan can expel returning vapor to the air through an exhaust manifold and scrub it through a biofilter, however one was not used at the site. Other odor management strategies include reducing the pile size and monitoring the moisture within the pile to prevent oversaturation. It is possible that higher methane generation potential exists in conventionally treated windrows, as regular aeration is not supplied, and anaerobic zones are more likely to form (Ma et al., 2020).

Facilitating desirable waste handling and storage

Compost aeration systems are designed to stabilize the manure and other biomass in the feedstock that contain P through drying and volume reduction; thus, simplifying storage, transportation, and redistribution. With a reduction in volume and the improved transport of the finished compost, compost aeration reduces excess phosphorous that can impair water quality by exporting it to where it can be beneficially utilized.

With the heat capture and redirection capability within the compost aeration and heat recovery system (Appendix C), heat can be redirected through the compost pile allowing the process to continue through the coldest months creating a year-round composting facility. Even without the heat recovery component, if the aerated compost process is started in the fall, temperatures within the pile will remain optimal, even in the coldest months, to allow for the composting process to continue. This allows producers to create a value-added product for growers that reduces nutrient losses throughout the planting season.

Producing value added byproducts that facilitate manure and waste utilization

Fully mature compost is similar in chemical and biological makeup regardless of the composting method; however, forced air composting dramatically shortens the process. The result of composting is an organic soil conditioner that has been stabilized into a humus-like product. The compost will be lighter and reduced in volume, have less plant and pathogen risk, won’t contain any viable seeds and will be much more stable than raw manure. The product will contain many essential nutrients that when applied to land will improve both the soils chemical and physical properties. Compost benefits field productivity by improving soil organic matter, nutrient availability and water holding capacity. Additionally, it can reduce erosion, disease and weed germination.

In the comparison study (Appendix C), the traditional windrow compost system performed slightly better, besting the aerated compost in N-P-K content by 2.7%, 15.9%, and 7.4%, respectively, however, time must be considered when interpreting these results. It is reasonable to conclude that the aerated compost system produced a comparable product in 13 weeks, four weeks shorter than the windrow treatment's 17 weeks to maturity. Additionally, when comparing the primary nutrient (N-P-K) values between treatments on an as-is basis, the aerated system was able to produce a nutritionally superior wet product, with respective N-P-K values 19.5%, 6.9%, and 15.3% higher than the windrow-treated counterparts.

RANGE OF VOLUMETRIC AND MASS FLOW CAPACITIES AS WELL AS HYDRAULIC RETENTION TIME

The scale of composting on a dairy is largely dependent on its individual manure management system (i.e. flush, scrape, flume, vacuum or a combination), size of the operation and economic viability of the composting solution.

- *Volumetric Flow*: Typical batch size 200 cubic yards based on solid feedstock mixture with a bulk density of 1000 lbs/cubic yard (CY) or less - actual operating ranges observed are 110 to 300 CY. Typical batch retention time is four weeks - actual operating ranges observed are two to 16 weeks. Annual volume composted in typical operating conditions - 20,800 CY/year - actual operating ranges observed are 14,000 to 30,000 CY/year for 8 zone systems.
- *Mass Flow*: Typical operating conditions would see 10,400 tons/year - based on average bulk density of 1000 lbs/CY of composting feedstocks.
- *Hydraulic Retention Times (HRT):* Hydraulic retention is not utilized within Compost Aeration systems. Only solid feedstocks are composted. Liquids are added to some mixtures, but blends remain in solid form not exceeding 65% moisture content.

DESIRED FEEDSTOCK CHARACTERISTICS

Feedstocks are raw, organic by-products used for composting. Typical feedstocks include livestock manure (solid and separated solids), food and yard waste, straw, grass clippings, sawdust and/or other by-products of wood processing. To ensure optimum success, several raw materials should be mixed to create the feedstock. On dairies, manure is typically combined with fibrous material, oftentimes cow bedding. The feedstock mixture must create a range of conditions within the pile including:

- feedstock made with optimal sized particles, typically less than an inch in diameter
- C:N nutrient balance around 20-40:1
- pile moisture content of 50 to 60% by weight
- oxygen (O_2) concentrations greater than 10%
- pH between 6.5 to 8.0
- temperatures between 130°F and 150°F.

EXPECTED SYSTEM PERFORMANCE

Although aerated composts may require more ardent monitoring, the time benefits of higher temperatures and constant aeration are noticeable. Typically, aerated compost is mature within two to four months, unlike windrow-treated compost that can take between six to twelve months. Due to the controlled flow of air, aerated composting allows for the construction of large piles, requiring less land than with traditional windrows. It should be noted that although most aerated composts are static piles, the system studied was turned as often as the traditional windrow in order to reduce the time required to operate the system, ensure that the entire pile was evenly composted, and get some of the added benefits of the heat recovery.

- *Changes in form or handling characteristics*
    - As carbon dioxide is released during the composting process, the pile size is reduced and the particle size of the feedstock is lighter and smaller in volume, causing the pile to settle. For manure feedstock, the volume and density are reduced by approximately 50-65%. The resulting compost should have a uniform appearance that is dark brown or black in color and possess an earthy smell with no ammonia odor.
- *Nutrient fate or end use projections*
    - The nutrients in mature compost are more stable and typically require a gradual release period of three or more years. Feedstock incorporating dairy manure contains nutrients such as nitrogen, phosphorous and potassium as well as a range of micronutrients and organic matter. After reaching maturity, the resulting pile will typically contain between 30-50% less carbon.
- *Macro-nutrient reductions or transformations*

    - Analysis of nitrogen species status throughout the study referenced in Appendix C suggests that greater nitrogen losses occurred during conventional treatment than during the aerated treatment, presumably due to higher rates of denitrification and ammonia volatilization. Data also suggest a lower risk for phosphorus loss through leaching from aerated-treated compost, as water extractable phosphorous concentrations were consistently higher in the conventional treatment.

- *Pathogen reductions or eliminations*
    - Compost aeration systems tend to have higher consistent temperatures and therefore, increased potential for pathogen kill. Composting decreases pathogens by up to 66% compared to recycled manure solids that are not composted.

- *Air emissions*
    - In a recent study by Wang et al. (2021), the authors concluded that intermittent aeration is a useful strategy in limiting ammonia (NH_3) and greenhouse gas (GHG) emissions as well as reducing carbon and nitrogen losses during aerated composting of cow manure. Though several factors affect gaseous emissions including C/N ratio, moisture content, pH and feedstock mix, aeration rate was considered a critical factor for determining nitrogen transformation and gaseous emissions. Deficient aeration rates can create anaerobic conditions leading to an increase in the emissions of methane (CH_4) and nitrous oxide (N_2O) as well as NH_3 volatilization.

- *Water quality*
    - Aerated composting provides a direct benefit to water quality impacts as it decreases leaching risks during storage and land application when compared with uncomposted manure. The lighter, more nutrient dense compost allows for easier transport which reduces over-application and enables better distribution of nutrients. This in turn reduces leaching of nitrates into the groundwater providing environmental and human health benefits.

PROCESS MONITORING AND CONTROL SYSTEM REQUIRMENTS

At its most basic level, aerated compost piles are regulated via temperature feedback. When the blower is on, the air will move through the pile, cooling the compost and adding oxygen to the pile. Installed systems are typically outfitted with main electrical control boxes with Programmable Logic Controllers (PLC) or automated controls that automatically regulate the system. Therefore, monitoring and control are simplified and partially adaptable to changing input flow conditions during continuous operation.

Aerated compost piles are highly dynamic microbial systems and monitoring and controlling for optimal conditions within the pile is not a static activity.

- *Required monitoring*— Batches are monitored for temperatures, oxygen levels and energy yields, structure, and odor, as well as any management practices that need refinement. Improvement of irrigation and moisture management has been identified as one means to further improve process efficiency.
- *Required control*—The blower settings will need to be controlled throughout the aeration process until a mature compost is reached.
- *Equipment included for monitoring*— Sensors to track temperature, oxygen levels, and vapor flow rates to guide the settings of operating controls. Data logging captures historical trends for guiding operation and tracking energy yields
- *Equipment included for controlling*— The blowers are controlled via an onsite or remote programmable logic controller with data logging capabilities. Timer settings control length of aeration cycle (negative aeration), duration of recirculation (positive aeration of heated exhaust vapor), and fan power/speed.

TYPICAL OPERATIONS/MAINTENANCE PLAN WITH MONITORING REQUIREMENTS AND REPLACEMENT SCHEDULE

This equipment has its own manufacture's O&M plan, monitoring requirements, and parts list with scheduled replacement. These are large documents and difficult to include with this submission but would be available upon request from any technology provider as well as available on-site at a project. Electronic and/or hard copies could be made available for this review upon request.

CHEMICAL INFORMATION

Chemical inputs are not utilized within Compost Aeration systems.

ESTIMATED INSTALLATION AND OPERATION COST

The following cost data is based on the CAHR system and may not be indicative of all Compost Aeration systems. Notably, differences will exist from specific technology provider and project, but the range is an initial best effort of categorizing the costs by range across scales.

Equipment and Installation Capital Costs

CAHR equipment comes in a range of sizes and Agrilab Technologies Inc. (AGT) also produces custom units. Standard commercial-scale models range from $72,000 to $169,000 (AGT Compost Hot Box 250-8RD). The two units at Foster Brothers Farms/VNAP with equivalent 8 zone capacity were sold and installed in 2016 and 2017 at a combined cost just under $120,000. Total installation capital costs for two phases of installation were approximately $400,000. Recent single-phase installation was completed for approximately $350,000. Use of buildings can significantly change the installation capital cost range.

Operation and Maintenance Costs (O&M)

- ***Electrical—*** $600/year based 24/7 operation of two 3hp motors.
- ***Labor—*** Variable but typical 1 hour/week of data observations and adjusting controls; compost processing labor typically reduced 25-50% versus prior turned windrow exclusively operation. (Connecticut Clean Energy Fund (CCEF) and Vermont Clean Energy Development Fund (CEDF) reports provided previously and available upon request).
- ***Maintenance Replacement—*** Variable O&M- $3000/year typical - parts, internal labor and contractors. Primary system components warrantied 5 years to meet USDA funding requirements. Wear items carry original equipment manufacturer warranties of 1 to 2 years (valve actuators, sensors, etc.).

EXAMPLE WARRANTY

Each technical approach commercialized within this class of technology will have its own warranty and warranty wording. However, expected warranties are as follows:

- Warranty against defects in the workmanship of equipment and components for a period of one (1) year from the date of installation.
- Obligation under warranty is limited to correcting, with no additional payment due from customer, any part or parts which shall be found defective or part or parts which have been installed improperly. Repair or replacement is at vendor's option.
- Vendor shall not be obligated to pay for, nor reimburse customer for, the cost of unauthorized repairs.
- This warranty is the sole and exclusive warranty given by vendor and in lieu of all other warranties.

RECOMMENDED RECORD KEEPING

A review of record keeping at facilities shows that beyond daily walk-through checklist items/observations related to the specific technology's operational procedures, the most often recorded information is as follows:

- Daily recording with time observation of temperatures within the pile.
- Daily recording with time observation of aeration schedule, moisture content, oxygen content, pile structure and odor.
- Recording of type and quantity of moisture added that day.
- Estimated volume/mass of compost produced with discussion on quality.
- Recording of specific maintenance work done that day and any working observations/concerns.

Ideally, the daily checklist recordings on hard copy paper are memorialized via electronic scans with an Excel spreadsheet totalizing data overtime.

ALTERNATIVES FOR THE USE OF BYPRODUCTS

- This class of technology produces a compost by-product from the treatment of the manure. More and more dairies are using recycled manure solids (RMS) or composted solids, for bedding in free stall barns to reduce costs and complexity associated with manure treatment when sand or other bedding is used. When not used as bedding, compost is typically used as a fertilizer to local fields, and with densification, is more suitable to be hauled to more distant fields for better maintenance of nutrient management plans or sold. There are other uses for composted solids, such as being used as a replacement for peat moss in potting soils or for erosion control.

INDEPENDENT VARIFIABLE DATA DEMONSTRATING RESULTS/CREDENTIALS

Appendix A is a summary of the independent review of peer-reviewed and technical data available for this class of technology and is available through Newtrient (2018). The Newtrient work involves an internal peer-review, comprised of ten national experts in the field of manure management, with the final output presently being prepared for external peer-review and publication. While the reference list is not a complete listing of all related peer-reviewed literature it does highlight key references specific to this class of technology and how it relates to key performance indicators within this NRCS 629 Standard.

Appendix B is a summary of data obtained during a Newtrient-managed third-party review of a compost aeration and heat recovery system in the U.S. at Vermont Natural Ag Products (VNAP) in Middlebury, VT. The information was from a 17-week analysis of the system and its performance by the University of Vermont—the work has not been peer-reviewed.

Appendix C is the complete UVM report detailing the third-party review at Vermont Natural Ag Products (VNAP) in Middlebury, VT.

CONTACT INFORMATION—VENDOR

While not an absolute conclusive list, the list below identifies vendors that are active in the application of this class of technology on manure projects within the US.

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- Agrilab Technologies, Inc. – Heat from Compost
  Agrilab Technologies Inc. standard products include the Drum Dragon, Hot Skid, Hot Box and AerSkid units. This technology incorporates aeration to accelerate the composting process for manure, bedding, forest residuals, food scraps and other biomass. Contact and product information available at:
  https://www.newtrient.com/catalog/agrilab-technologies-inc-heat-from-compost/
- Engineered Compost Systems
  Engineered Compost Systems develops and manufactures technology and provides technical services for large-scale composting facilities. Contact and product information available at:
  https://compostsystems.com/about/
- Green Mountain Technologies
  Green Mountain Technologies has developed a comprehensive product line that includes sophisticated large-scale technologies for biosolids, windrows, Aerated Static Pile (ASP) solutions, cutting-edge software and probes and some of the most popular in-vessel systems in the country. Contact and product information available at:
  https://www.compostingtechnology.com/mission/
- O2Compost
  O2Compost specializes in designing compost systems to process virtually all organic residuals, including food waste, landscaping debris, animal manure, biosolids and other source separated organics. Contact and product information available at:
  https://www.o2compost.com/why-o2compost.aspx

CONTACT INFORMATION—USER

Commercial facilities presently operating in the US with this class of technology are identified below. The list is a best effort but may not be completely inclusive of all installations.

<u>Compost Aeration and Heat Recovery (CAHR) Technology</u>

Country Oaks Landscape Supply - Burton, Michigan

Tamarlane Farm - Lyndonville, VT

Catlin Farm – Winchendon, MA

Foster Brothers Farm - Middlebury, VT

Vern Mont Farm - Vernon VT

City Soil & Greenhouse - Boston, MA

Organic Dairy Research Farm - Durham, NH

Jasper Hill Farm - Greensboro, VT

Sunset View Farm - Schaghticoke, NY

Diamond Hill Custom Heifers - Enosburg Falls, VT

OTHER CONSIDERATIONS

The NRCS documentation specifies that a third-party review shall contain 15 specific items that comprise the report above, but as part of working with the farm(s) and the technology provider during the 17-week evaluation period there are often other important and valuable learnings that may be helpful for NRCS and others as they consider this technology. Below is a list of Other Considerations that should be included in the evaluation of this technology:

- Temperature Stratification – A key metric of a forced aeration system's efficiency is its ability to maintain target temperature ranges throughout the pile. For example, in the comparison study, it was quickly noted that in the windrow treatment, temperature stratification was occurring within the windrow, likely due to low average oxygen levels at different depths from the windrow surface. To create an aggregate temperature for the windrow treatment, two temperatures were taken and averaged for each sample point. One temperature reading at approximately 8”-12” from the surface, where oxygen was likely plentiful and temperatures were higher, and one temperature reading at the full 36” depth. As expected for the aerated treatment, temperature stratification was not observed.

- Compost Temperature and Moisture Content – Composting efficiency relies heavily on process conditions such as temperature, oxygen, pH and moisture. In the comparison study, aerated-treated compost sustained higher internal temperatures than were observed in the windrow treatment. Because compost batches were mixed a few days before sampling began, initial compost temperatures had already risen well above ambient temperatures. Higher temperatures combined with constant aeration led to a consistently drier material for the aerated treatment. Therefore, VNAP staff increased monitoring to ensure temperatures did not rise too high and moisture contents did not drop too low. It should be noted that with more ardent monitoring, the time benefits of higher temperatures and constant aeration reduce composting time and therefore, over drying.

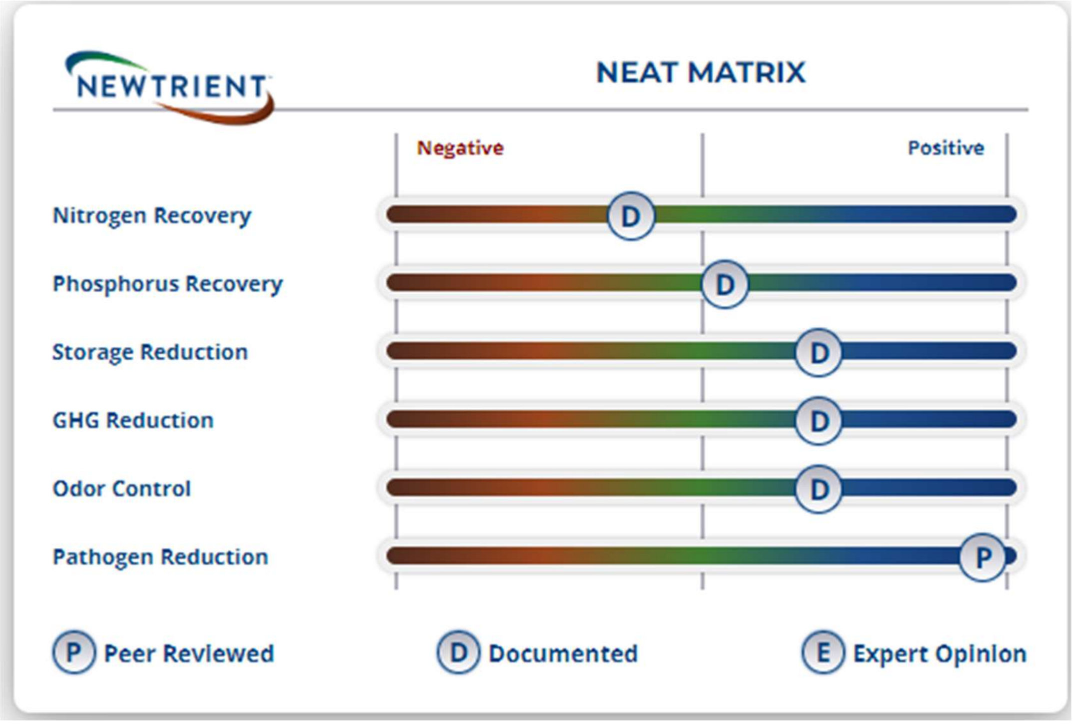
- Pathogen Growth – Fecal coliforms surprisingly increased over the comparison study, namely for the CAHR system, which provided higher consistent temperatures and potential for pathogen kill. Because fecal coliform data were only obtained for the first few and last samples of each treatment, trends were not established. Increases in fecal coliform data could have arisen from a few sources, namely high bird activity at VNAP, localized high levels of coliforms that happened to be randomly sampled, and any pathogen growth between when frozen samples were shipped from UVM to when they were analyzed at the lab.

Conclusion

Aerated composting is a method of composting that utilizes forced air to accelerate the composting cycle and reduce odor by optimizing oxygen levels in the pile. These systems reduce labor and increase processing yields, all while helping to protect land and waterways. Additionally, aerated compost systems have the potential to decrease overall operational cost and increase revenue from sales of high-quality compost.

Appendix A

NEWTRIENT CRITICAL INDICATOR ANALYSIS—COMPOSTING



Overall Summary

Dairy manure contains most of the macro and micronutrients needed to support healthy plant growth; however, raw manure poses pathogen risks for crops grown for human consumption, poses storage and handling problems, and can contaminate soil with excess nutrients. Aerated composting is a composting system that uses forced air to accelerate the decomposition process resulting in a finished, humus-rich product with little to no ammonium or soluble nitrate. Mature compost provides a less dense, nutrient-rich product that reduces many of the drawbacks of raw manure.

Forced aeration compost systems optimize the composting process by evenly distributing air throughout the pile, most commonly by using a pipe-on-grade system with positive, negative, or reversing aeration (alternates between positive and negative). During composting, aerobic bacteria begin to break down the feedstock causing a depletion of oxygen and a rapid rise in temperatures within the pile. Aeration supplies optimal oxygen saturation levels, optimizing the pile, creating a more efficient biostabilization and diminishing odor emissions.

The advantage of using this type of compost system is that compost treated with forced air is suitable for market in much less time than a conventionally turned windrow, with less nitrogen loss. The quicker maturation, and reduced exposure time of an aeration system to precipitation reduces the time in which leaching, and surface runoff can occur; thus, reducing nutrient loss to surrounding waterways and producing a water quality benefit. The disadvantages associated with aerated compost systems include the high cost of infrastructure and management, the utilization of solid manure only and potential air emissions and water quality impacts.

Research shows that undesirable nitrogen losses via nitrate-leaching and gaseous emissions (including emissions of nitrous oxide) were likely curtailed because aeration was more effective in preserving nitrate and nitrite-oxygen during the composting process. Additionally, aerated-treated compost provided better protection against phosphorus loss through leaching, possibly through immobilization by microbial communities and more stable redox-sensitive iron-phosphate due to more prominent aerobic conditions (Appendix C).

References

Ma, S., Xiong, J., Cui, R., Sun, X., Han, L., Xu, Y., Kan, Z., Gong, X., & Huang, G. (2020). Effects of intermittent aeration on greenhouse gas emissions and bacterial community succession during large-scale membrane-covered aerobic composting. Journal of Cleaner Production, 266. https://doi.org/10.1016/j.jclepro.2020.121551

Wang, Y.; Qiu, H.; Li, M.; Ghanney, P. Influence of Aeration Method on Gaseous Emissions and the Losses of the Carbon and Nitrogen during Cow Manure Composting. Appl. Sci. 2021, 11, 11639. https://doi.org/10.3390/app112411639

Yang, X., Liu, E., Zhu, X., Wang, H., Liu, H., Liu, X., & Dong, W. (2019). Impact of composting methods on nitrogen retention and losses during dairy manure composting. International Journal of Environmental Research and Public Health, 16(18), 1–17. https://doi.org/10.3390/ijerph16183324

Appendix B

Third-Party Review of Compost Aeration and Heat Recovery (CAHR) System at Vermont Natural Ag Products (VNAP) in Middlebury, VT. (Report Summary)

Figure 1 is a side-by-side comparison of the conventional windrow composting pile (image on the left - initial volume 480.2 CY) and the Compost Aeration and Heat Recovery system compost pile (image on the right - initial volume 548.8 CY).

Figure 1. Left Image: Non-CAHR treated windrow. Right Image: CAHR-treated windrow. Images from Vermont Natural Ag Products' (VNAP) compost facility in Middlebury, Vermont.

OVERVIEW

Vermont Natural Ag Products, Inc. (VNAP), a subsidiary of the Foster Brothers Farm, Inc. in Middlebury, Vermont, is a fifth-generation family farm in Vermont's beautiful Champlain Valley, owned and operated by Bob Foster and his family. Beginning in 1941 with a single-story barn and herringbone parlor, the farm now has a 475-cow "Cow Palace", of which more than 370 are milked, and almost 2,000 acres of crops. Foster Brothers Farm is committed to sustainable farming practices and was recognized as the 2019 Innovative Dairy Farmer of the Year presented by the International Dairy Foods Association.

As innovators in dairy sustainability, the Foster's along with Agrilab Technologies Inc., designed and installed a manure Compost Aeration and Heat Recovery system (CAHR) at their compost facility in Middlebury, VT, to produce energy and more efficiently compost manure solids. Foster Brothers' VNAP is the state's largest composting facility; processing dairy, poultry and horse manure, forest product residuals, source-separated food scraps and other biomass into a variety of compost and soil products.

As organic waste streams become increasingly abundant with increases in human population and livestock rearing, so increases the need for efficient management of these wastes. Organic wastes such as manure, biomass, food scraps, and straw, among others, hold immense value as compost feedstocks. Compost is a valuable soil additive for agricultural producers and homeowners alike, but compost generation is not without challenges and is a time and space-intensive process. New technologies such as CAHR are emerging that have the potential to ease budgetary pressure and reduce time and space requirements for compost producers. Therefore, the objective of this study was to evaluate nutrient status, financial cost, and energy cost for a CAHR system to develop a mature compost in comparison to conventional windrow manure composting where aeration only occurs via turning.

BACKGROUND

Compost treated with a CAHR system was suitable for market in approximately 75% of the time as a conventionally turned windrow, with less nitrogen loss.

In 2016 and 2017, VNAP partnered with Agrilab Technologies on the installation and use of CAHR systems to optimize oxygen levels and therefore accelerate the composting process, and additionally to capture and utilize thermal energy which is a natural co-product of the active decomposition process. The heat is then used for heating facilities, drying products prior to screening and bagging, and extending full composting operations throughout winter. CAHR has been fully operational at VNAP since 2018 and has proven effective at reducing VNAP's expenditures on #2 heating oil, propane, diesel fuel, and labor (Foster et al., 2018).

The quicker maturation, and reduced exposure time of a CAHR system to precipitation, was expected to reduce the time in which leaching, and surface runoff can occur; thus, reducing nutrient loss to surrounding waterways and producing a water quality benefit. To test this hypothesis quantitatively, metrics that proxy phosphorous leaching risk were calculated, using data collected on water-extractable phosphorous mass, duration of composting, and precipitation, and were then compared across systems. Cost data was also collected and analyzed for each system.

The basic design of the CAHR system (Figure 1) includes compost windrows placed on a paved pad containing a shallow trench oriented longitudinally with the windrow. The trench contains perforated HDPE piping bedded in wood chips. These pipes are connected to solid, insulated HDPE piping which runs to a shipping container outfitted with circulation fans and a heat exchanger. While the circulation fans are negatively aerating (i.e., pulling vapor from) the compost, warm vapor entering the system transfers heat energy to water piped through the heat exchanger. Heat recovered from compost windrows has been used to heat the site's bagging building via radiant floor heating and to dry finished compost prior to the screening and bagging process. Furthermore, due to elevated oxygen levels provided by positive and negative aeration, CAHR-treated compost has been reported to mature more quickly and require less turning, reducing diesel, labor, and equipment maintenance costs (Foster et al., 2018).

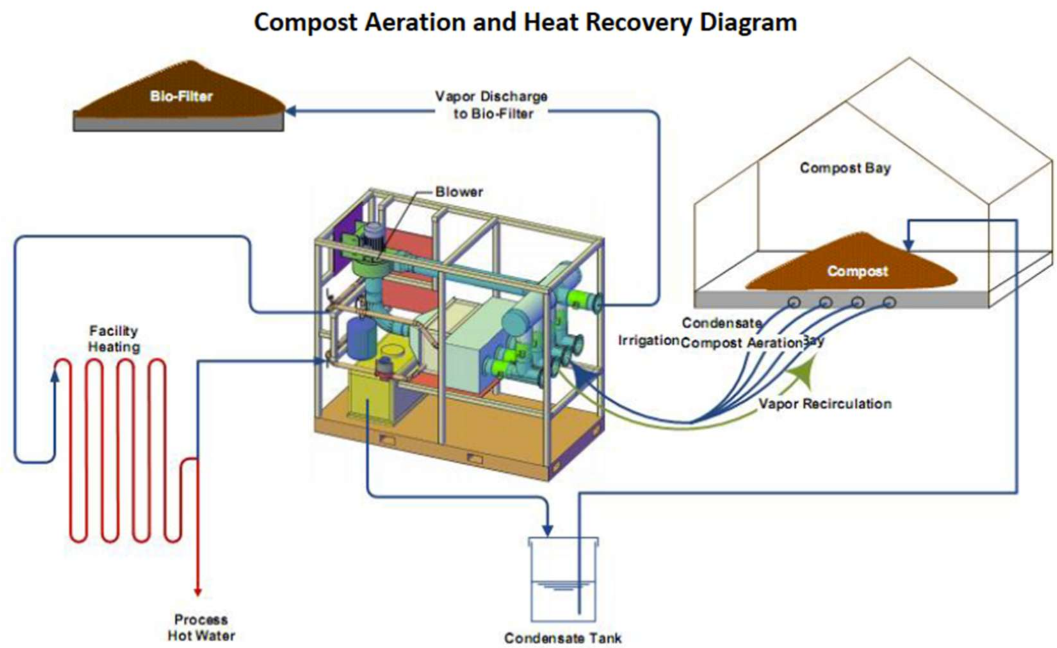


Figure 2. Compost aeration and heat recovery diagram.

The CAHR system is set up with four zones of perforated piping. At any given time, one of three scenarios is typically taking place.

1. Vapor is pulled from one zone, run through the heat exchanger, and exhausted to the environment;
2. Fresh air is pulled from the environment and used to positively aerate one zone; or
3. Vapor is pulled from one zone, run through the heat exchanger, and pushed into another zone.

In addition to warming the receiving zone, this configuration is hypothesized by VNAP to help "seed" a microbial community in an immature compost windrow, accelerating the process.

In the comparison study, two compost windrows of equivalent feedstock contents and ratios were monitored. The control windrow, denoted as “TRAD”, was a conventionally treated windrow that did not receive aeration aside from periodic windrow turning with a Komptech Topturn x53 compost turner. The experimental windrow, denoted as “CAHR”, received periodic positive and negative aeration via the CAHR system, as well as aeration through periodic turning. The initial volumes of the TRAD and CAHR windrows were 480.2 CY and 548.8 CY, respectively.

The initial feedstock composition of both windrows was as follows:

- Sawdust: 46.7%
- Dairy manure: 23.3%
- Dairy bed pack: 23.3%
- Chicken manure: 5.8%
- Wood ash: 0.9%

KEY ISSUES AND CHALLENGES

The composite aeration and heat recovery systems became fully operational in 2018, with VNAP assuming responsibility for ongoing system operations and maintenance.

During the study, several key operational issues were identified and addressed as outlined below.

Temperature Stratification – A key metric of a forced aeration system’s efficiency is its ability to maintain target temperature ranges throughout the pile. For the TRAD treatment, it was quickly noted that temperature stratification was occurring within the windrow, likely due to low average oxygen levels at different depths from the windrow surface. To create an aggregate temperature for the TRAD treatment, two temperatures were taken and averaged for each sample point. One temperature reading at approximately 8”-12” from the surface, where oxygen was likely plentiful and temperatures were higher, and one temperature reading at the full 36” depth. As expected for the CAHR treatment, temperature stratification was not observed.

Compost Temperature and Moisture Content – Composting efficiency relies heavily on process conditions such as temperature, oxygen, pH and moisture. The CAHR-treated compost sustained higher internal temperatures than were observed in the conventional treatment. Because compost batches were mixed a few days before sampling began, initial compost temperatures had already risen well above ambient temperatures. Higher temperatures combined with constant aeration led to a consistently drier material for the CAHR treatment. Therefore, VNAP staff increased monitoring to ensure temperatures did not rise too high and moisture contents did not drop too low. It should be noted that with more ardent monitoring, the time benefits of higher temperatures and constant aeration reduce composting time and therefore, over drying.

Pathogen Growth – Fecal coliforms surprisingly increased over the study, namely for the CAHR system, which provided higher consistent temperatures and potential for pathogen kill. Because fecal coliform data were only obtained for the first few and last samples of each treatment, trends were not established. Increases in fecal coliform data could have arisen from a few sources, namely high bird activity at VNAP, localized high levels of coliforms that happened to be randomly sampled, and any pathogen growth between when frozen samples were shipped from UVM to when they were analyzed at the lab.

SAMPLING PROGRAM AND RESULTS

The University of Vermont (UVM) provided the sampling, testing and recording of the compost from the two composting systems. For the first thirteen weeks of the sampling period, composts from a CAHR-treated windrow and a conventionally treated windrow without aeration except for turning, were sampled thrice weekly for both treatments. The windrows were comprised of identical feedstocks and feedstock ratios and were batched simultaneously by VNAP. At the end of the thirteenth week, VNAP deemed the CAHR treatment compost suitable for market and pulled it for processing. Sampling continued once weekly for the TRAD treatment for another four weeks, when the TRAD windrow was pulled for processing. Overall, this resulted in a total of 43 samples of TRAD and 39 samples of CAHR composts.

To establish sampling points, an (x,y,z) coordinate system was established for each treatment based on windrow dimensions. For each sampling instance, a randomized set of 8 (x,y,z) coordinates was generated, and a 5-gallon sample was taken from each sample point with a steel drain spade and pail. For each treatment, samples were composited on a tarp and mixed vigorously, resulting in 40 gallons of composited sample. From each composite, a two-gallon sub-sample was collected and kept frozen prior to analysis, and a one-quart sub-sample was collected and kept refrigerated prior to analysis.

At each sample point, a 36" compost probe thermometer was used to gather manual temperature data. For the TRAD treatment, it was quickly noted that temperature stratification was occurring within the windrow, likely due to varied oxygen levels at different depths from the windrow surface. Given this, for the TRAD treatment, one temperature reading was taken at approximately 8"-12" from the surface, where oxygen was likely plentiful and temperatures were higher, and one temperature reading was taken at the full 36" depth. These two temperatures were averaged for each sample point to create an aggregate temperature. For the CAHR treatment, temperature stratification was not observed, and a single temperature reading was taken at 36" depth at each sample point.

Once weekly, an in-situ bulk density estimate was taken for each of the 5-gallon samples taken. Bulk density was established using the "partial fill and drop" method outlined by Washington State University (Washington State University, 2021).

MAJOR COMPOST TESTING OVERALL PERFORMANCE RESULTS

Tables 1 and 2 below show the major compost testing metrics on a dry weight and as-is (wet) basis, respectively. Values included in these tables are from the initial and final sampling dates for each treatment. These data provide a succinct method of comparing the resulting composts produced by each treatment method.

Table 1. Dry weight basis compost test parameters, first and last days of study.

Dry Weight Basis		**TRAD**		**CAHR**	
Test Parameter	Units	Initial value on 8/24/2021	Final value on 12/15/2021	Initial value on 8/24/2021	Final value on 11/19/2021
Total N	%	1.42	2.62	1.44	2.55
Total Kjeldahl N	%	1.45	2.49	1.32	1.99
Nitrate + Nitrite N	%	below detection	0.13	0.12	0.56
Nitrate + Nitrite N	% of TN	below detection	4.96	8.33	21.96
Phosphorus	%	0.42	1.00	0.54	0.87
WEP	mg P /kg	885	869	1083	841
P as WEP	% of TP	21	9	20	9
Potassium	%	1.18	2.46	1.25	2.29
N-P-K	%	1.42-0.42-1.18	2.62-1.00-2.46	1.44-0.54-1.25	2.55-0.87-2.29
Total Organic C	%	45.28	40.5	46.79	44.38
C:N Ratio	-	31.2	15.5	32.5	17.4
N:P Ratio	-	3.38	2.62	2.67	2.93
pH	-	8.1	7.8	8.3	7.5

Fecal Coliforms	MPN/g dry	2	10	2	4430

When comparing N-P-K by dry weight basis in Table 1, we see that the conventionally treated compost was slightly superior, besting the CAHR compost in N-P-K content by 2.7%, 15.9%, and 7.4%, respectively. Time must be considered when interpreting these results, and it is reasonable to conclude that the CAHR system produced a comparable product in 13 weeks, four weeks shorter than the conventional treatment's 17 weeks to maturity.

However, when comparing the primary nutrient (N-P-K) values between treatments on an as-is basis in Table 2, it is seen that the CAHR system was able to produce a nutritionally superior wet product, with respective N-P-K values 19.5%, 6.9%, and 15.3% higher than the conventionally treated counterparts.

Table 2. As-is compost test parameters, first and last days of study.

As-is Basis		**TRAD**		**CAHR**	
Test Parameter	Units	Initial value on 8/24/2021	Final value on 12/15/2021	Initial value on 8/24/2021	Final value on 11/19/2021
Moisture Content	%	64.73	70.53	64.22	63.85
Total N	%	0.50	0.77	0.52	0.92
Total Kjeldahl N	%	0.51	0.73	0.47	0.72
Nitrate + Nitrite N	%	below detection	0.04	0.05	0.20
Nitrate + Nitrite N	% of TN	N/A	5.19	9.62	21.74
Phosphorus	%	0.15	0.29	0.19	0.31
WEP	mg P/kg	312	256	387	304
P as WEP	% of TP	21.16	10.34	21.05	9.68
Potassium	%	0.42	0.72	0.45	0.83
N-P-K	%	0.50-0.15 -0.42	0.77-0.29-0.72	0.52-0.19-0.45	0.92-0.31-0.83
Total Organic C	%	15.97	11.94	16.74	16.04
C:N Ratio	-	31.2	15.5	32.5	17.4
N:P Ratio	-	3.33	2.66	2.74	2.97
pH	-	8.1	7.8	8.3	7.5

A mass balance was performed for major compost nutrients, shown in **Table 3** below. Colorized columns show the nutrient retention percentages for each treatment. Interestingly, values above 100% were computed for many parameters, which would suggest nutrient input. This is unlikely, however, since there are no pathways for N, P, and K input from the atmosphere within the conditions of this study. Errors contributing to these calculations most likely lie in the bulk density values or in error associated with measurement of initial and final cubic yard values. Nutrient addition through watering with lagoon leachate was not considered consequential for mass balance. For example, 2.59 kg of N were added to the conventional windrow through watering, which would account for only 0.29% of the total N calculated for the finished windrow.

However, some general trends can be assessed. Of N, P, and K, the only mass loss estimated (i.e., mass retention <100%) was for N in the conventional treatment. There were many pathways for nitrogen to be lost in this system but given the NOx-N dynamics, it is likely that the conventional windrow suffered more N losses through denitrification than the CAHR windrow, with nitrate leaching and/or ammonia volatilization also possibly playing a role. The conventional windrow was also more susceptible to environmental losses due to an additional 4 weeks of composting time.

It can be reasoned that the CAHR system had higher carbon retention due to the shorter composting duration, allowing the conventional windrow more time to continue oxidizing organic matter. This is supported by the final C:N ratio values.

Table 3. Mass balance for major compost nutrients.

Mass Balance		**TRAD**			**CAHR**		
Test Parameter	Units	Initial value on 8/24/2021	Final value on 12/15/2021	**Retention (%)**	Initial value on 8/24/2021	Final value on 11/19/2021	**Retention (%)**
Bulk Density	lb/CY	910	1106	N/A	869	967	N/A
Windrow Volume	CY	480	234	**49**	549	320	**58**
Nitrogen	kg	991	903	**91**	1125	1291	**115**
Phosphorus	kg	297	340	**114**	411	435	**106**
Potassium	kg	833	845	**101**	973	1165	**120**
Total Organic Carbon	kg	31665	14009	**44**	36206	22514	**62**

SYSTEM ECONOMICS

In addition to laboratory testing and analyses of nutrient content, a cost and consumables analysis was performed to compare operational and energy costs between the CAHR and conventional treatments. Results of this analysis are provided in **Table 4**, with the following operational activities and assumptions considered:

- Compost turning with the Komptech Topturn x53 straddle turner
    - 10 L/hr fuel use during turning, provided by VNAP
    - 6.5 minutes to turn a 200' windrow, provided by VNAP
    - $60/hr operator wage, provided by VNAP
    - 9 turning events for the conventional windrow
    - 8 turning events for the CAHR windrow
- Compost watering with a 4400-gallon liquid manure tanker
    - 5L/hr fuel use during watering, estimated as half of turner fuel use rate
    - 20 minutes to fill and dispense 4400 gallons of liquid leachate, timed by FB
    - $60/hr operator wage, provided by VNAP
    - 1 watering event of 4400 gallons for the conventional windrow
    - 2 watering events of 4400 gallons for the CAHR windrow
- Aeration by the CAHR system
    - 746-watt (1 hp) power draw by the aeration fan, provided by Agrilab Technologies
    - 12 hours of aeration for the CAHR test window/day
    - 88 days of aeration for the CAHR test windrow
    - 17.33 cents/kWh average commercial electric rate in VT, provided by US EIA

Table 4. Operational financial and energy costs in the conventional and CAHR composting systems.

	TRAD		CAHR	
CY finished compost	234		320	
Operational Activity	Financial cost ($)	Energy Cost (kWh)	Financial cost ($)	Energy Cost (kWh)
Compost Turning	$ 58.50	103.71	$ 52.00	92.18
Compost Watering	$ 20.00	17.73	$ 40.00	35.46
Aeration Blower Fan	$ -	0.00	$ 136.52	787.78
Total	**$ 78.50**	**121.44**	**$ 228.52**	**915.42**
Total (per CY finished compost)	**$ 0.34**	**0.52**	**$ 0.71**	**2.86**

From both an energy and financial cost standpoint, this analysis suggests that the conventional management of composts is less expensive than using the CAHR system.

Note: calculations only account for normal operational inputs from the time compost batches were assembled until they were removed from production. This study did not account for any time and space savings provided by a managed aeration system and did not include the energy and cost savings benefits of the CAHR system to an agricultural producer or waste manager, which have been well documented at VNAP and are summarized in Table 5 below (Foster et al., 2018).

Table 5. Cost savings per cubic yard of finished compost for the CAHR composting system relative to the conventional system.

Cost Savings Parameter	CAHR
Operational cost savings	$ (0.37)
Energy/Heating cost savings (Foster, et al., 2018)	$ 2.05
Avoided infrastructure cost savings (Foster, et al., 2018)	$ 2.38
Total savings (per CY finished compost)	**$ 4.06**

Considered in the energy and heating cost savings were the reduced demand for #2 heating oil used to heat the VNAP bagging building and propane used to dry composts prior to bagging. Heat captured from composts by the CAHR system reduced demand for those two fuel sources. The avoided infrastructure cost savings approximate projected expansion expenses that VNAP avoided through adoption of the CAHR system. If the CAHR system were not implemented, the facility would need to be expanded, as a greater pad area and lagoon volume would be required to process traditionally turned windrows while still meeting annual product demand.

Note: cost savings estimates are based on 2018 unit prices for #2 heating oil, propane, permitting, and earthwork, among others.

KEY LEARNINGS

1. CAHR treated compost produced a comparable product to the conventionally turned windrow in approximately 75% of the time.
2. Undesirable nitrogen losses via nitrate-leaching and gaseous emissions (including emissions of nitrous oxide) were likely curtailed because CAHR treatment and associated aeration was more effective in preserving nitrate and nitrite-oxygen during the composting process.
3. The data indicate that CAHR treated compost provided better protection against phosphorus loss through leaching, possibly through immobilization by microbial

communities and more stable redox-sensitive iron-phosphate due to more prominent aerobic conditions.

4. Though operating costs for CAHR compost were 2.1 times more expensive and 5.5 times more energy-intensive than a conventional compost on a per cubic yard basis, the energy and infrastructure cost offsets provided by the CAHR system (as operated at VNAP) could provide a net savings of $4.06/CY finished compost.
5. Either compost treatment, when applied to agricultural land, would likely release less phosphorus as water extractable phosphorus during rainfall events than direct manure application, providing water quality benefits.

KEY BENEFITS

Renewable thermal energy capture – CAHR systems are designed to capture renewable thermal energy via a specialized heat exchanger into a hydronic system (typically water and glycol loops). This heat can be utilized in a variety of ways including heating buildings via radiant floor heating, drying finished compost or preheating water for washing or other on-site processes.

Accelerated compost process – The CAHR composting system accelerates and provides more control over the composting process than a conventionally turned windrow. The rate of manure and biomass decomposition is directly related to the availability of oxygen through aeration. The CAHR aeration systems are designed to pull and/or push air (negative and positive aeration) through blended feedstocks, maintaining target temperatures throughout the pile. Composting time, as well as over drying, are reduced by the benefits of higher temperatures and constant aeration.

Reduction in nutrient leaching – Nutrient leaching from compost is often of concern as it is a common source of pollution and eutrophication. As noted above, CAHR-treated compost had less nitrogen and phosphorous loss than the traditionally treated compost, yet it produced a mature compost with comparable soil health and fertility benefits. The quicker maturation, and reduced exposure time of a CAHR system to precipitation, reduces the time in which leaching, and surface runoff can occur. Additionally, the potential to export off the farm can provide significant phosphorus reductions necessary to meet the state's clean water goals.

Savings in both energy and costs – This study only evaluated the costs of the operational inputs from the time the compost was in production, indicating the CAHR treatment was not the most economical option. However, once the time and space as well as the energy and cost savings benefits of the CAHR system were included in the overall analysis, the CAHR system was shown to generate significant savings. The reduced demand for #2 heating oil for the bagging building and drying compost contributed to energy and heating cost savings. Additionally, less labor was required to operate the managed aeration system and implementing the CAHR system reduced the need to expand the VNAP facility to accommodate additional traditional windrows, providing both operational and infrastructure cost savings (Foster, et al., 2018).

CONCLUSION

This study evaluated nutrient status, financial cost, and energy cost for a pair of commercial compost windrows in a normal production setting. From a time and space management standpoint, compost treated with a forced-aeration system was deemed suitable for market in approximately 75% of the time as a conventionally turned windrow; 13 and 17 weeks, respectively. Analysis of nitrogen species status throughout the study suggests that greater nitrogen losses occurred during conventional treatment than during CAHR treatment, presumably due to higher rates of denitrification and ammonia volatilization. Data also demonstrated a lower risk for phosphorus loss through leaching from CAHR-treated compost, as water extractable phosphorus (WEP) concentrations were consistently higher in the conventional treatment. During the active composting process, it was found that operational costs for CAHR compost were 2.1 times more expensive financially and 5.5 times more energy-intensive than a conventional compost on a per CY basis. However, the energy and infrastructure cost offsets provided by the CAHR system (as operated at VNAP) could provide a net savings of $4.06/CY finished compost. In this study, it was shown that a CAHR system produced a comparable compost product, with higher operational input, in less time.

Furthermore, the data suggest that land application of either compost treatment evaluated in this study may reduce phosphorus loss due to leaching versus direct manure application. For example, WEP concentrations in the finished composts in this study ranged between 0.256 and 0.304 g/kg on a dry weight basis, while WEP concentrations in dairy manures have been found to range between 1.98 and 4.0 g/kg (P. Kleinman et al., 2007; P. J. A. Kleinman et al., 2005). It is probable that either compost treatment, when applied to agricultural land, would release less phosphorus as WEP during rainfall events than direct manure application, providing water quality benefits.

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Appendix C

Third-Party Review of Compost Aeration and Heat Recovery (CAHR) System at Vermont Natural Ag Products (VNAP) in Middlebury, VT. (Full Report)

EVALUATION OF AGRICULTURAL NUTRIENT MANAGEMENT TECHNOLOGIES AT VERMONT NATURAL AG PRODUCTS, MIDDLEBURY, VERMONT

Prepared by: Finn Bondeson, Joshua Faulkner, and Eric Roy

ABSTRACT

This study evaluated nutrient status, financial cost, and energy cost for an existing manure Compost Aeration and Heat Recovery system (CAHR) by Agrilab Technologies, Inc. at the Vermont Natural Ag Products (VNAP) compost facility in Middlebury, Vermont in comparison to conventional windrow manure composting where aeration only occurs via turning. From a time and space management standpoint, compost treated with a forced-aeration system was deemed suitable for market in approximately 75% of the time as a conventionally turned windrow. Analysis of nitrogen species status throughout the study suggests that greater nitrogen losses occurred during conventional treatment than during CAHR treatment. Data also suggest a lower risk for phosphorus loss through leaching from CAHR-treated compost, as WEP concentrations were consistently higher in the conventional treatment. Operational costs for CAHR compost were 2.1 times more expensive financially and 5.5 times more energy-intensive than a conventional compost on a per cubic yard basis. However, the energy and infrastructure cost offsets provided by the CAHR system (as operated at VNAP) could provide a net savings of $4.06/CY finished compost. In this study, it was shown that a CAHR system produced a comparable compost product, with higher operational input, in less time.

Furthermore, the data suggest that land application of either compost treatment evaluated in this study may reduce phosphorus loss due to leaching versus direct manure application. It is probable that either compost treatment, when applied to agricultural land, would release less phosphorus as WEP during rainfall events than direct manure application, providing water quality benefits.

INTRODUCTION

The objective of this study was to evaluate nutrient dynamics and operational costs within an existing manure Compost Aeration and Heat Recovery system (CAHR) by Agrilab Technologies, Inc. at the Vermont Natural Ag Products (VNAP) compost facility in

Middlebury, Vermont in comparison to conventional windrow manure composting where aeration only occurs via turning. Constructed in 2016 and 2017, the CAHR has been fully operational since 2018 and has proven effective at reducing VNAP's expenditures on #2 heating oil, propane, diesel fuel, and labor (Foster et al., 2018).

The basic design of the CAHR system includes compost windrows placed on a paved pad containing a shallow trench oriented longitudinally with the windrow. The trench contains perforated HDPE piping bedded in wood chips. These pipes are connected to solid, insulated HDPE piping which runs to a shipping container outfitted with circulation fans and a heat exchanger. While the circulation fans are negatively aerating (i.e. pulling vapor from) the compost, warm vapor entering the system transfers heat energy to water piped through the heat exchanger. Heat recovered from compost windrows has been used to heat the site's bagging building via radiant floor heating and to dry finished compost prior to the screening and bagging process. Furthermore, due to elevated oxygen levels provided by positive and negative aeration, CAHR-treated compost has been reported to mature more quickly and require less turning, reducing diesel, labor, and equipment maintenance costs (Foster et al., 2018).

The CAHR system is set up with four zones of perforated piping. At a given time, one of three scenarios is typically taking place.

- Vapor is pulled from one zone, run through the heat exchanger, and exhausted to the environment.
- Fresh air is pulled from the environment and used to positively aerate one zone.
- Vapor is pulled from one zone, run through the heat exchanger, and pushed into another zone. In addition to warming the receiving zone, this configuration is hypothesized by VNAP to help "seed" a microbial community in an immature compost windrow, accelerating the process.

While the financial benefits of the CAHR at VNAP have been documented, a comparison of nutrient content of CAHR-treated and non-CAHR-treated composts has not been undertaken. The primary objective of this study was to determine how well, and how quickly, the CAHR system created a mature compost with soil health and fertility benefits as compared to a conventional composting system. To test this hypothesis quantitatively, we measured several metrics that collectively approximate phosphorus and nitrogen contents and loss risk over time, as well as the overall compost maturation timeline, and compared these metrics across systems. Cost and energy use data were also collected and analyzed for each system.

1. METHODS

The protocol for this study was adapted from "Protocol for Third Party Evaluation of Agricultural Nutrient Management Technologies" (Bronstad et al., 2019).

1.1 STUDY SITE

This evaluation was undertaken at the Vermont Natural Ag Products composting facility in Middlebury, Vermont. VNAP produces compost products in batched windrows, with feedstocks sourced regionally from livestock producers, forest products processors, agricultural fairs, and food waste diversion programs.

1.2 STUDY GROUPS

Two compost windrows of equivalent feedstock contents and ratios were monitored. Our control, denoted as "TRAD", was a conventionally treated windrow that did not receive aeration aside from periodic windrow turning with a Komptech Topturn x53 compost turner. Our experimental windrow, denoted as "CAHR", received periodic positive and negative aeration via the CAHR system, as well as aeration through periodic turning. The initial volumes of the TRAD and CAHR windrows were 480.2 CY and 548.8 CY, respectively.

The initial feedstock composition of both windrows was as follows:

- Sawdust: 46.7%
- Dairy manure: 23.3%
- Dairy bed pack: 23.3%
- Chicken manure: 5.8%
- Wood ash: 0.9%

1.3 SAMPLING AND IN-SITU DATA COLLECTION

Compost samples were collected between August 24th, 2021, and December 15th, 2021. For the first thirteen weeks of the sampling period, samples were taken thrice weekly from both treatments. At the end of the thirteenth week, on November 19th, VNAP staff deemed the CAHR treatment compost suitable for market and it was pulled for processing. Sampling continued once weekly for the TRAD treatment for another four weeks, terminating on December 15th, when the TRAD windrow was pulled for processing. This resulted in a total of 43 samples of TRAD and 39 samples of CAHR composts.

To establish sampling points, an (*x,y,z*) coordinate system was established for each treatment based on windrow dimensions. For each sampling instance, a randomized set of 8 (*x,y,z*) coordinates was generated, and a 5-gallon sample was taken from each sample point with a steel drain spade and pail. For each treatment, samples were composited on a tarp and mixed vigorously, resulting in 40 gallons of composited sample. From each composite, a two-gallon sub-sample was collected and kept frozen prior to analysis, and a one-quart sub-sample was collected and kept refrigerated prior to analysis.

At each sample point, a 36" compost probe thermometer was used to gather manual temperature data. For the TRAD treatment, it was quickly noted that temperature stratification was occurring within the windrow, likely due to varied oxygen levels at different depths from the windrow surface. Given this, for the TRAD treatment, one temperature reading was taken at approximately 8"-12" from the surface, where oxygen was likely plentiful and temperatures were higher, and one temperature reading was taken at the full 36" depth. These two temperatures were averaged for each sample point to create an aggregate temperature. For the CAHR treatment, temperature stratification was not observed, and a single temperature reading was taken at 36" depth at each sample point.

Once weekly, an in-situ bulk density estimate was taken for each of the 5-gallon samples taken. Bulk density was established using the "partial fill and drop" method outlined by Washington State University (Washington State University, 2021).

1.4 ATMOSPHERIC DATA COLLECTION

An Onset HOBO UA-003-64 data logger and accompanied tipping bucket rain gauge were deployed on August 24th, 2021, concurrent with the beginning of the sampling period. Data were downloaded from this logger on September 24th, November 1st, and December 29th. Rainfall during a short period between October 30th and November 1st was not recorded by the HOBO due to file size limits being exceeded. Rainfall data from the nearby Middlebury State Airport (approximately 1.5 miles SE) was sourced from the National Oceanic and Atmospheric Administration's Climate Data Online Search to fill this data gap.

An Onset HOBO external temperature and relative humidity sensor was deployed on October 7th, 2021. Deployment was delayed due to supply chain issues which permeated the scientific instrumentation market in 2021. Data were downloaded from this logger on December 29th, but file storage had been exceeded on December 8th and recording was terminated. Hourly temperature data from the nearby Middlebury State Airport were sourced from the National Oceanic and Atmospheric Administration's Climate Data Online Search to fill the August 24th-October 7th and December 8th-December 15th data gaps.

1.5 SAMPLE ANALYSIS

All frozen two-gallon samples were sent to A&L Great Lakes Laboratories (A&L) in Fort Wayne, IN for commercial compost analysis. The initial and final samples of each treatment, in addition to samples from collection days 2, 3, 6, and 7 were tested for constituents in A&L's C10 testing package, which includes the following: solids/moisture content, total nitrogen, phosphorus, potassium, potash, calcium, magnesium, pH, soluble salts, organic matter, total organic carbon, C:N ratio, fecal coliforms, aggregate size distribution, germination, respiration, foreign material, and 503 heavy metals. All other samples were tested for constituents in A&L's C6 testing package, which includes the following: solids/moisture content, total nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, sodium, iron, aluminum, manganese, copper, zinc, organic matter, total organic carbon, C:N ratio, pH, and soluble salts (A&L Great Lakes Laboratories, 2022). Total Kjeldahl nitrogen was analyzed once weekly and for the initial and final samples of each treatment. All testing performed by A&L followed procedures outlined in the US Composting Council's *Test Methods for the Examination of Composting and Compost.*

All refrigerated one-quart samples were held for no longer than 72 hours before analysis for water extractable phosphorus (WEP). This analysis was performed at the University of Vermont following Kleinman et al. (2007). In summary, 10g-15g of each sample were weighed in triplicate and dried at 60° C for 18 hours to determine moisture and solids content. Extracting vessels were filled with compost sample and deionized water to achieve a 2:200 mass ratio of solids (by dry-weight basis) to liquids. The suspensions were shaken for one hour after which the supernatants were vacuum filtered at 0.45 µm. Filtered supernatant samples were frozen and stored for analysis to determine soluble reactive phosphorus (SRP) using the colorimetric malachite green method (Lajtha et al. 2009).

1.6 NUTRIENT MASS BALANCE APPROXIMATIONS

The following equation was used to approximate total nitrogen, phosphorus, potassium, and carbon masses contained in each treatment at the beginning and end of the study:

$$Nutrient\ mass\ (kg) = Nutrient\ content\ (as - is)\ (\frac{kg}{kg}) \times Compost\ density\ \left(\frac{lb}{CY}\right) \times \frac{1\ kg}{2.205\ lbs} \times Windrow\ volume\ (CY)$$

After mass approximations were made, the following equation was used to determine nutrient mass retention:

$$\%\ Nutrient\ retention = \frac{Nutrient\ mass\ (final)}{Nutrient\ mass\ (initial)} \times\ 100$$

It should be noted that because the 5-gallon sample volumes used to calculate bulk density are orders of magnitude smaller than the volumes of the windrows, any errors in bulk density measurements are compounded. Caution should be taken during interpretation of the mass balance figures. Nutrient contents used in the calculations above were "as is" values (i.e., mass nutrients per wet-basis mass of compost at the moisture content observed in the sample).

1.7 ENERGY AND EXPENSE MONITORING

Data quantifying energy use and expenses associated with each treatment were gathered from VNAP and Agrilab Technologies. Each compost turning event was recorded, and associated fuel use and labor expenses were calculated for each treatment during the study. Agrilab Technologies assisted with electrical calculations associated with the operation of the CAHR system.

The following two conversion rates were gathered from the US Energy Information Administration (US EIA) to normalize all energy consumption to kWh: *1 kWh = 3412 Btu* & *1 gallon diesel fuel = 137,381 Btu.*

2. NUTRIENT AND COMPOST METRICS RESULTS & DISCUSSION

Nutrient composition and other compost data gathered during this study were compiled in an Excel spreadsheet and plots were produced in R. Manual temperatures and nutrient data shown are averages of the three sample points taken weekly. Unless otherwise indicated, nutrient concentrations in plots and tables are expressed in percent nutrient by dry mass of compost. Representing nutrient composition on a percent dry weight basis normalizes the results, allowing us to compare the two treatments independent of moisture content. Plots showing nutrient trends by mass of "as-is" compost (i.e., wet mass of compost at the moisture level during time of sampling) are provided in Attachment A.

2.1 COMPOST TEMPERATURE AND MOISTURE CONTENT

As can be seen in **Figure 1** below, the CAHR-treated compost sustained higher internal temperatures than were observed in conventional treatment. Microbial communities in the CAHR system were provided with more oxygen, which in theory should increase microbial activity and in turn temperature (Yang et al., 2019). Note that because compost batches were mixed a few days before sampling began, initial compost temperatures had already risen well above ambient temperatures.

Figure 2 demonstrates the rapid decrease in moisture content following initially high aggregate temperatures in the thermophilic phase: maximum of 145.9 °F for conventional treatment and 171.1 °F for CAHR. The conventionally treated and CAHR treated windrows each observed similar trends in moisture content and temperature over time, and the influence of rainfall on moisture content is evident. However, higher temperatures combined with constant aeration led to a consistently drier material for the CAHR treatment.

More careful monitoring of the CAHR compost was needed by VNAP staff to ensure temperatures did not rise too high and moisture contents did not drop too low, both factors which could have negative outcomes on microbial communities in the compost (Onwosi et al., 2017). On September 15th, 2021, VNAP staff watered the CAHR-treated windrow with ~8800 gallons of leachate from the onsite stormwater runoff lagoon using a liquid manure tanker. The conventionally treated windrow received ~4400 gallons. Composts were immediately turned to integrate the irrigated liquid, and a sample of the leachate used was collected and sent for analysis at A&L Labs. Nutrient contents in the leachate were determined negligible for consideration in this study. A copy of the leachate nutrient report is included in Appendix C.

Although CAHR-treated composts may require more ardent monitoring, the time benefits of higher temperatures and constant aeration were noticeable. The CAHR-treated windrow composted faster was deemed suitable for market by VNAP 4weeks before its conventionally treated counterpart.

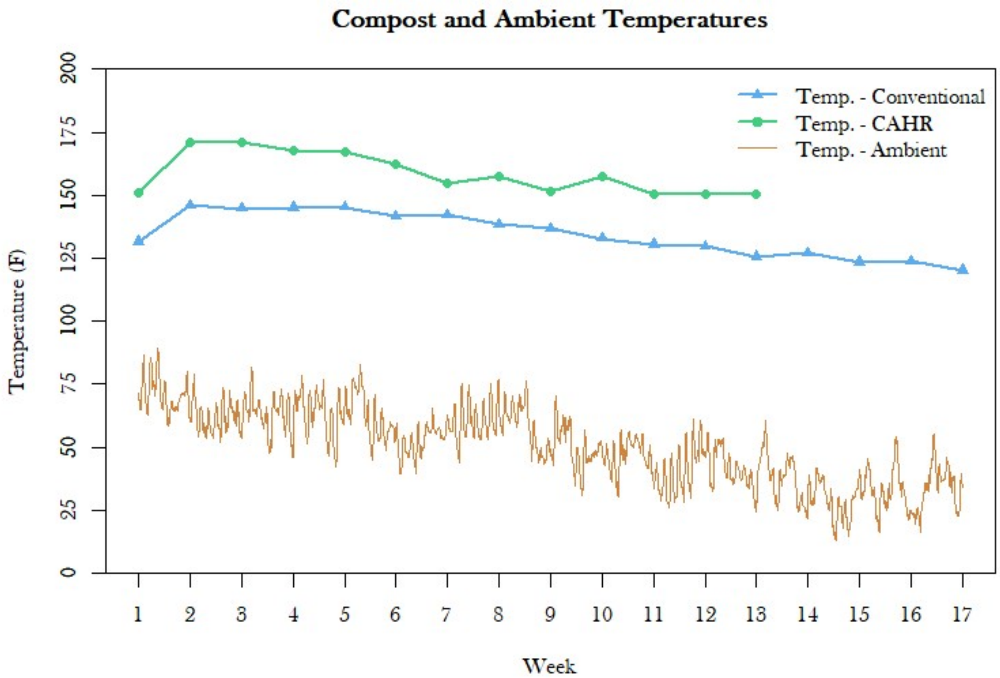


Figure 1. Temperature over time in the conventional and CAHR compost windrows.

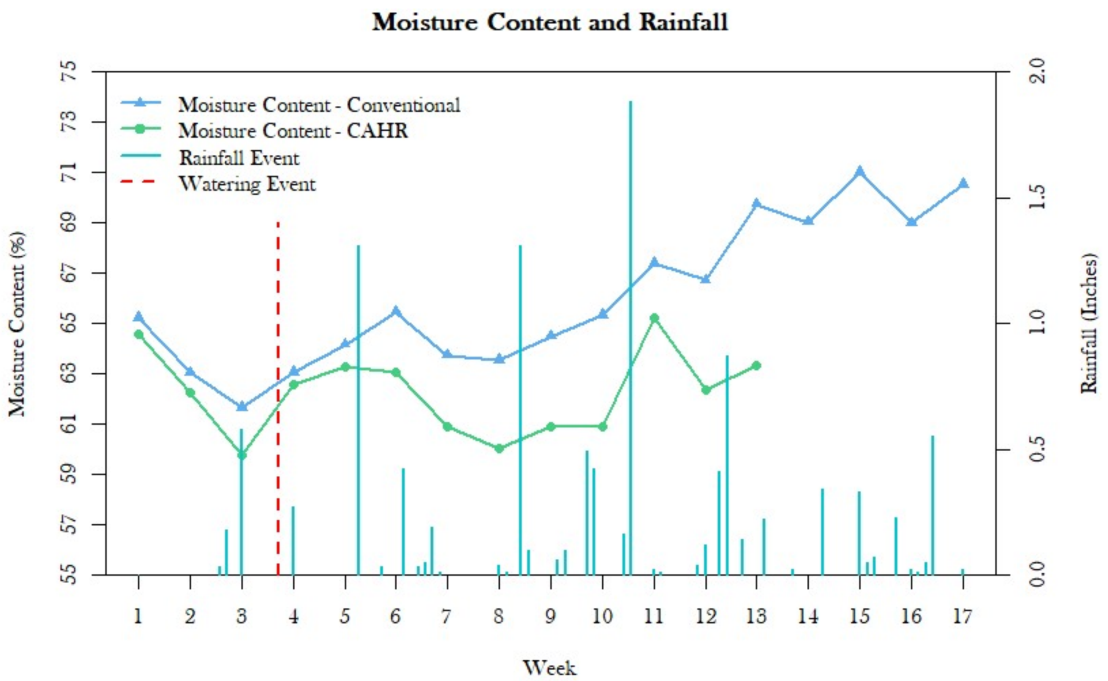


Figure 2. Rainfall events and moisture contents over time in the conventional and CAHR compost windrows.

2.2 CARBON DYNAMICS

Because the compost process is dependent on microbial communities oxidizing carbon sources in the feedstocks and respiring CO_2 under aerobic conditions, we expect carbon losses to occur (Bernal et al., 2017). Total organic carbon (TOC) relationships between composts are shown in **Figure 3**. We see nearly identical trends in TOC concentrations between the treatments, suggesting similar microbial degradation rates between the treatments, which is surprising given higher temperatures noted in the CAHR treatment. As can be expected, the conventional treatment resulted in a lower TOC fraction, as microbes had a longer time to consume organic matter.

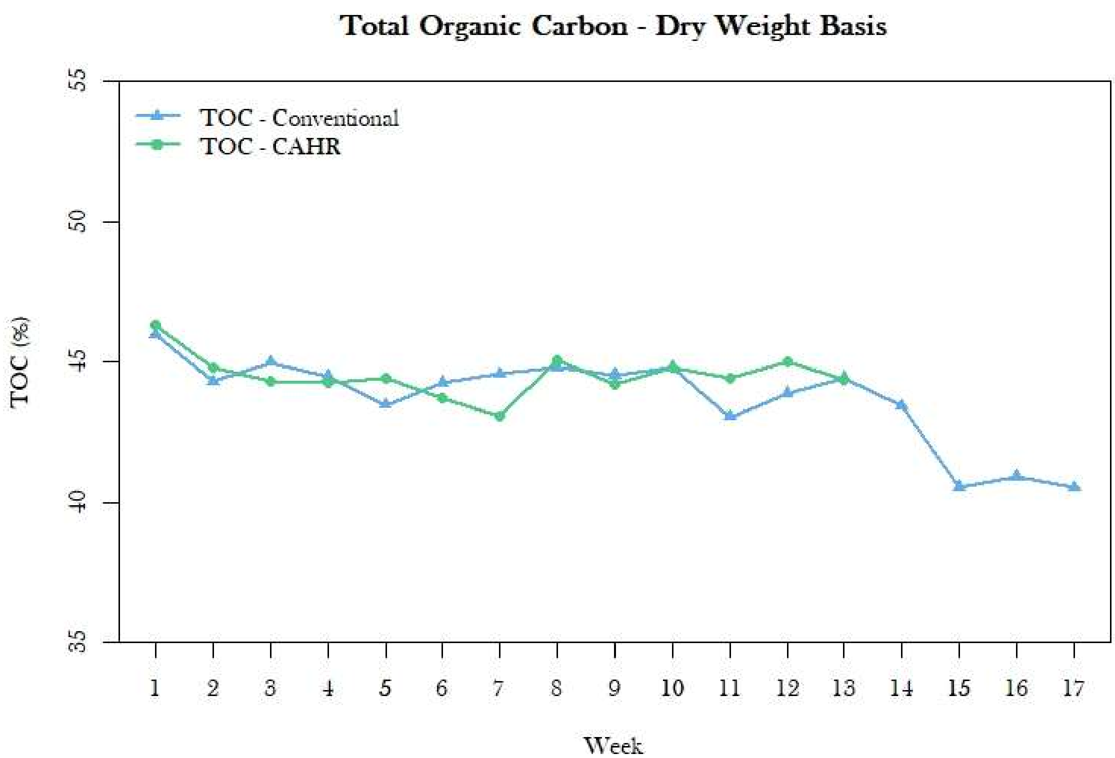


Figure 3. Total organic carbon (TOC) in the conventional and CAHR compost windrows.

Carbon to nitrogen ratio (C:N) began at 31:1 for the conventional windrow and 33:1 for the CAHR windrow, which is typical of fresh compost mixes at VNAP. Because nitrogen concentrations increased more rapidly in the CAHR treatment, we saw the C:N ratio drop more rapidly throughout the early weeks of the study, as shown in **Figure 4**. Referencing Figure 2, we see that between weeks 10 and 11, C:N ratios dropped more slowly in the CAHR treatment, which displayed a greater gain in moisture content over this time.

Overall, a slightly lower C:N ratio was achieved for finished compost from the conventional windrow (16:1) than the CAHR windrow (17:1), which can be attributed to the conventional windrow having four additional weeks of composting time. It is suggested by Bernal et al. (2009) that a C:N ratio below 20:1 can be a suitable metric for determining compost maturity. This metric of maturity suggests that the CAHR compost reached maturity by week 11, 3 weeks before the conventional windrow.

As we did not perform gaseous analysis as a component of this study, we cannot determine which treatment may have been more prone to carbon loss through methane release. It is possible that higher methane generation potential existed in the conventionally treated windrow, as regular aeration was not supplied, and anaerobic zones were more likely to form (Ma et al., 2020).

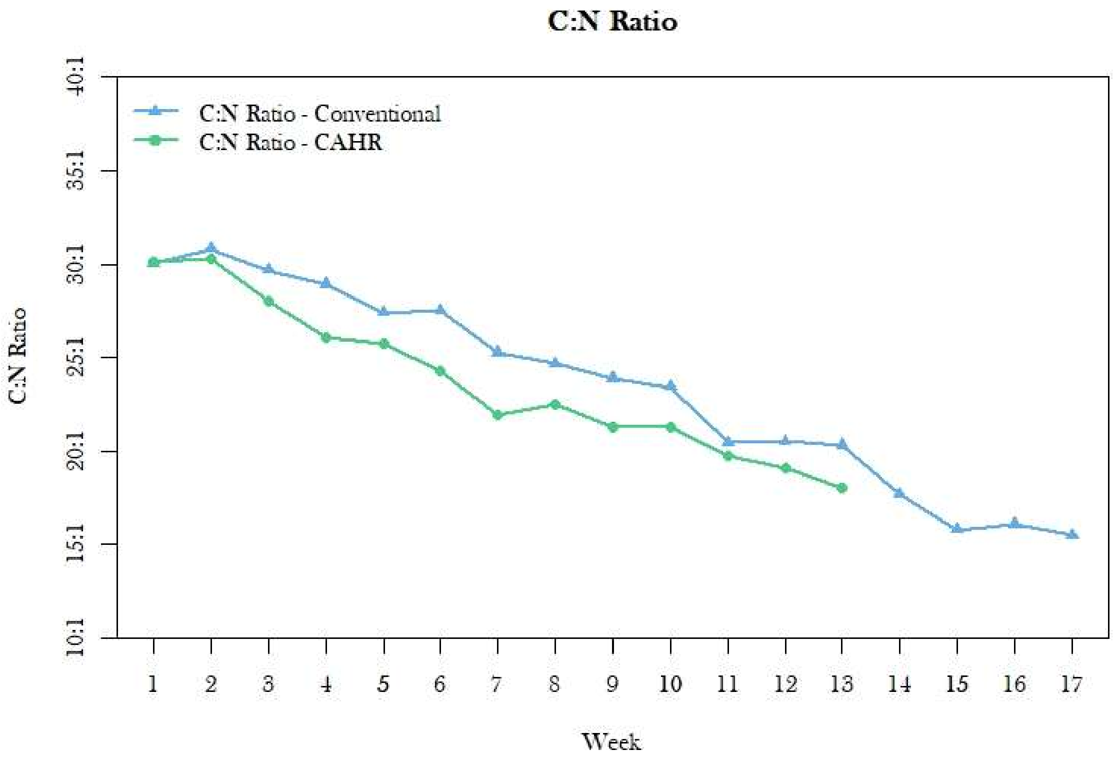


Figure 4. C:N ratios in the conventional and CAHR compost windrows.

2.3 NITROGEN DYNAMICS

Total nitrogen (TN) concentrations in the composts both increased over time, as can be seen in **Figure 5** below. Since microbial communities rely on oxidation of carbon as an energy source, nitrogen (along with other nutrients and inorganic constituents) was concentrated in both composts over time. Coincident with the high temperatures around week 2, we observed that TN percentages increased more quickly in the CAHR compost than the traditionally treated compost. Trends were similar, but it is evident that frequent aeration facilitated more preservation of nitrogen, especially early in the study. Conventional treatment resulted in an end product with an overall higher nitrogen concentration on a dry weight basis.

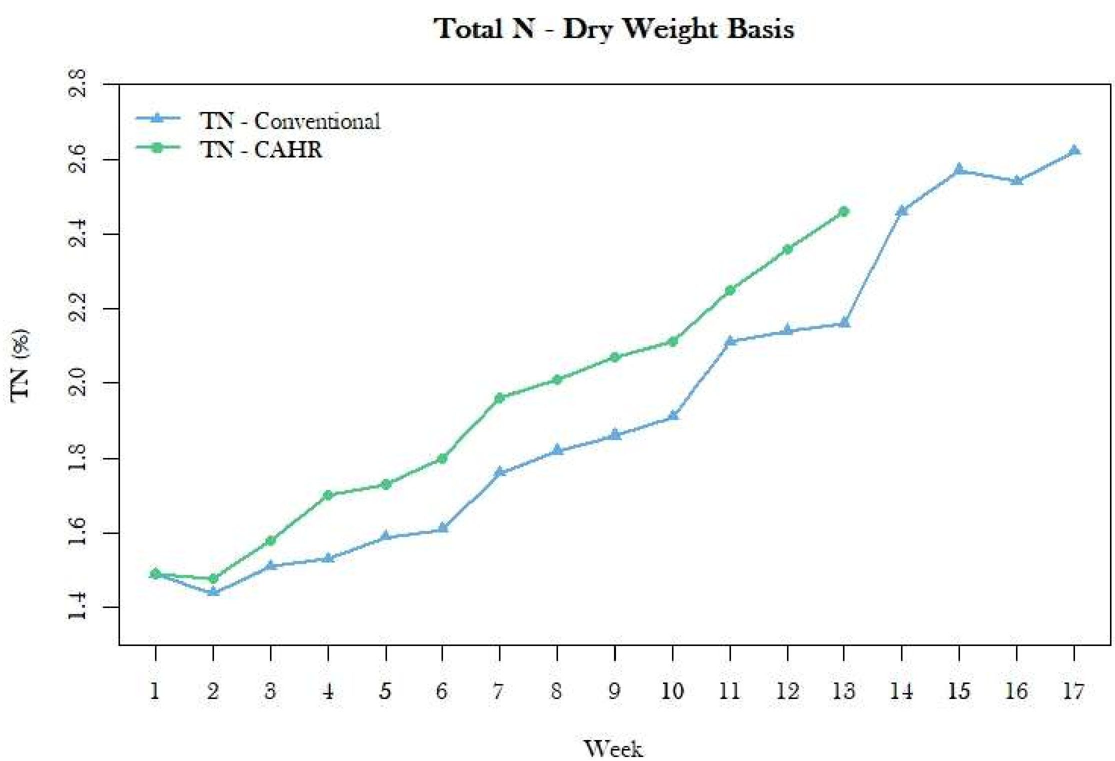


Figure 5. Total nitrogen in the conventional and CAHR compost windrows.

Total Kjeldahl nitrogen (TKN) relationships are shown in **Figure 6**. TKN is the sum of organic nitrogen and ammonia nitrogen but differs from TN in that it does not include nitrate nitrogen (NO_3-N) or nitrite nitrogen (NO_2-N). It is seen that TKN values track similarly week-to-week between treatments. TKN was measured once weekly, so less smooth results can be expected. Given that TN is TKN plus NO_x-N (NO_2-N + NO_3-N), and TKN concentrations behaved similarly between the two treatments, NO_x-N analysis can provide valuable insight as we evaluate possible causation for the gap between TN trends seen in Figure 5.

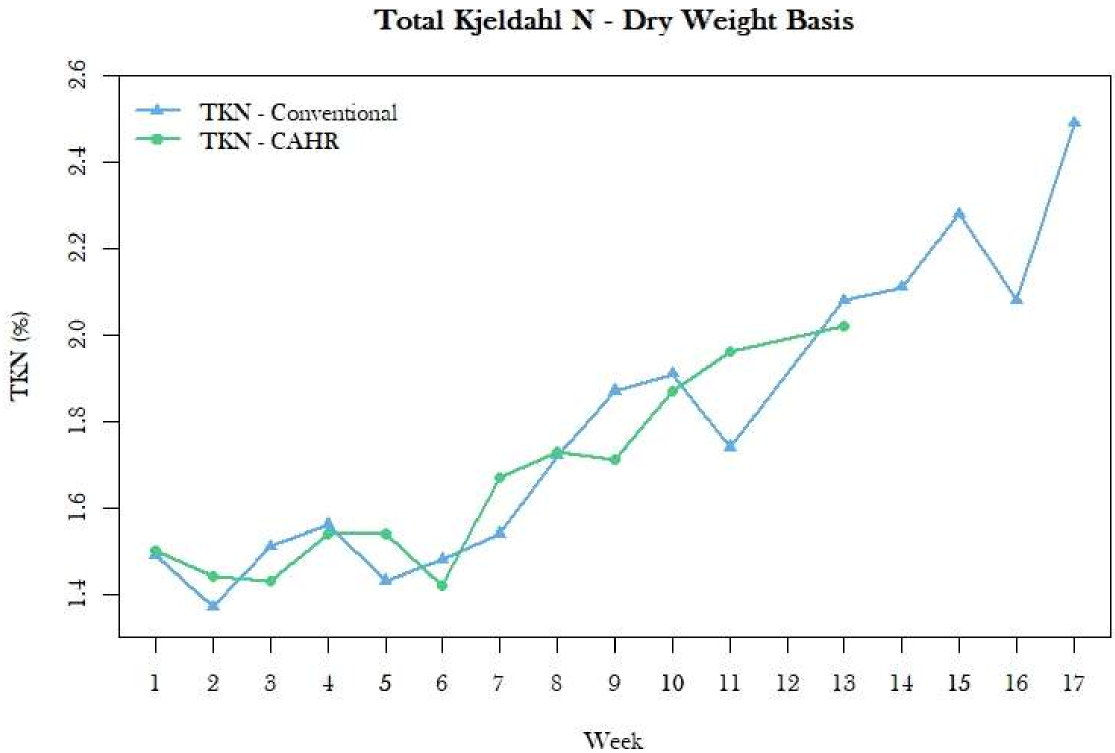


Figure 6. Total Kjeldahl nitrogen in the conventional and CAHR compost windrows.

Figure 7 (below) shows the relationships between NO_x-N and moisture content for both composts. With the context of rainfall and turning events (**Figure 8**) in mind, we can begin to assess nitrogen dynamics. Nitrate nitrogen is a highly available nitrogen source for plants and is ideal to preserve in composts. NO_2-N and NO_3-N are produced by nitrifying bacteria in the presence of oxygen, but can be lost through leaching (i.e., during heavy rain events) or through denitrification the absence of oxygen, when NO_3-N can be converted to gaseous forms of nitrogen, including dinitrogen gas (N_2) and nitrous oxide (N_2O), the latter being a potent greenhouse gas (GHG) (Johnson et al., 2005; Yang et al., 2019).

In the conventionally treated windrow, we can see multiple instances of NO_x-N increasing as moisture contents decreased and decreasing as moisture contents increased. When NO_x-N decreased, it is possible that some NO_3-N was lost to the environment through leaching, but more was likely lost as gaseous forms of N. Because the conventionally treated windrow received less oxygen and was more likely to form anaerobic zones (especially when wet), we hypothesize that more denitrification, which requires anaerobic conditions, may have occurred in the conventional windrow, and that gaseous N losses resulted. While N_2 is the dominant end product of denitrification, fugitive N_2O emissions can also occur due to incomplete denitrification (note: N_2O emissions can also result from incomplete ammonium oxidation) (US EPA, 2020). The sharp drop in NO_x-N concentrations between weeks 2 and 4 in the conventional treatment was not seen in the CAHR windrow, which explains the CAHR's higher rate of TN increase during this time.

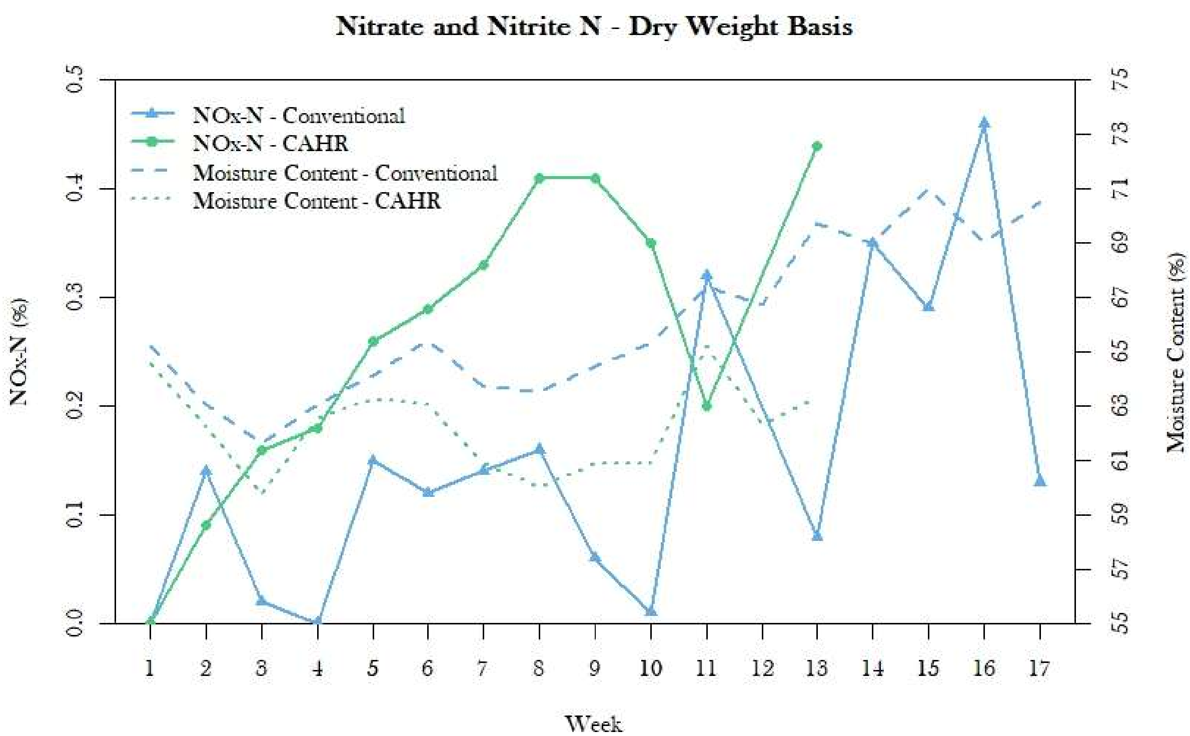


Figure 7. Nitrate + nitrite N (NO_x-N) in the conventional and CAHR compost windrows.

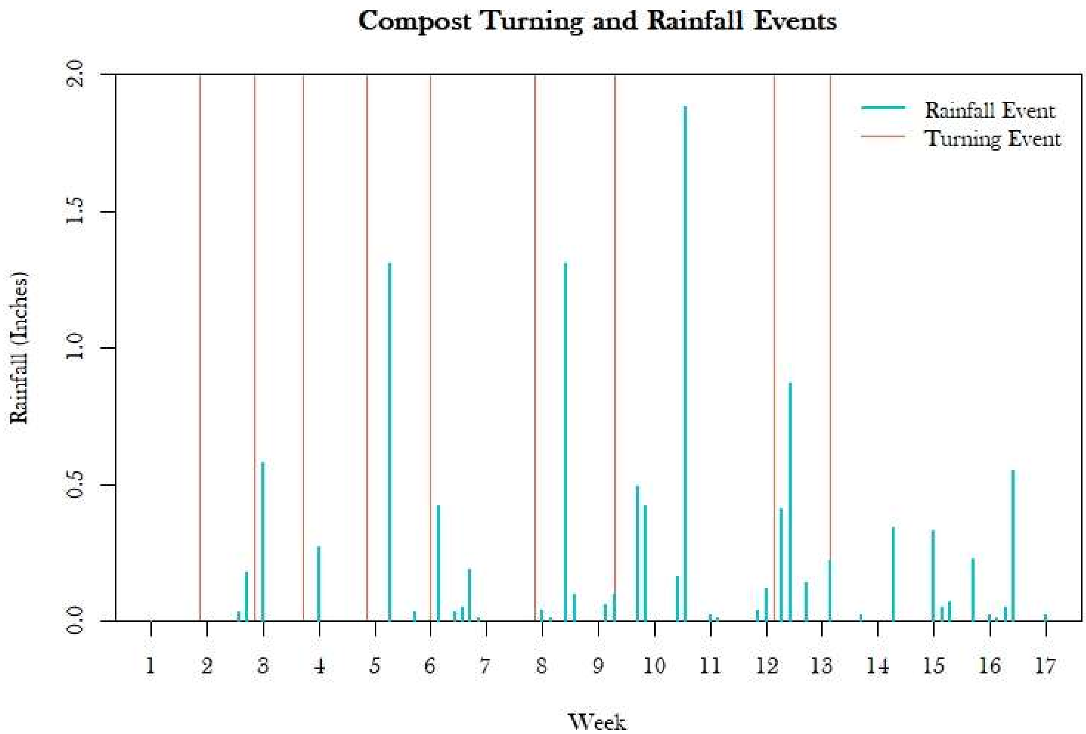


Figure 8. Rainfall and turning events in the conventional and CAHR compost windrows.

We observed NO_x-N losses for only a short period in the CAHR windrow, between weeks 8 and 11, as moisture content consistently increased. The large rainfall event between weeks 10 and 11 may have facilitated NO_3-N leaching and denitrification in the CAHR treatment but appeared to facilitate nitrification in the conventional windrow based on a decrease in TKN (Figure 6). Overall, the data largely suggest that the CAHR treatment and associated aeration was more effective in preserving NO_x-N during the composting process, thereby likely curtailing undesirable N losses via NO_3^- leaching and gaseous emissions (including emissions of N_2O). Further research is needed to confirm these dynamics. Another possibility for TN loss from the conventional windrow is ammonia volatilization. If the conventional windrow was losing ammonia and the CAHR windrow was more effectively converting ammonium to nitrate, these two different processes – if of a similar magnitude - could result in similar TKN concentrations between the treatments despite the overall loss of N from the conventional windrow.

2.4 PHOSPHORUS DYNAMICS

As was seen in TN concentrations over time, total phosphorus (TP) increased in magnitude as carbon sources in the composts were metabolized. In **Figure 9**, we see only slight differences between traditional and CAHR-treated composts' TP concentrations, with the conventionally treated windrow trending higher than the CAHR treatment in the final weeks of the study, most probably due to increased composting duration.

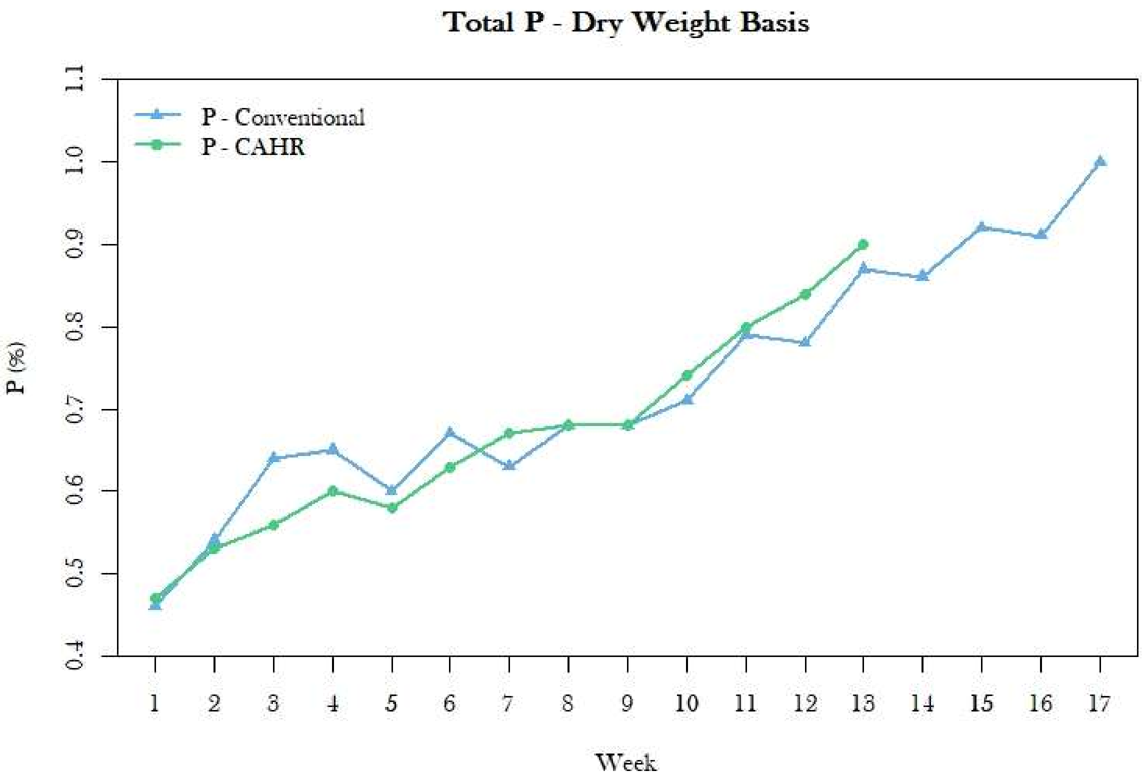


Figure 9. Phosphorus in the conventional and CAHR compost windrows.

Figure 10 shows water extractable phosphorus (WEP) concentrations over time. WEP is the portion of TP most available to plants but is susceptible to leaching loss, and thereby was the only way for phosphorus to be lost from these composts (Hyland et al., 2005). There is no pathway for phosphorus to be lost to the atmosphere through volatilization. Our results show the CAHR treatment providing consistently lower levels of WEP throughout the study. A portion of WEP in both treatments was lost, presumably to leaching, during the heavy rainfall event between weeks 10 and 11, but the data suggest that the CAHR treatment lost less WEP during this rainfall event.

To assess the characteristics of phosphorus in each compost, as well as its susceptibility to leaching, we calculated the percentage of total phosphorus that existed as WEP. As can be seen in **Figure 11**, CAHR-treated compost had a consistently lower percentage of

WEP than did the conventional treatment from week 4 on. These data suggest that the CAHR treatment provided better protection against phosphorus loss, possibly through immobilization by microbial communities and more stable redox-sensitive Fe-P due to more prominent aerobic conditions. Conventional treatment resulted in a slightly higher percentage of total P and WEP, but CAHR treatment seemed to be less prone to P leaching losses.

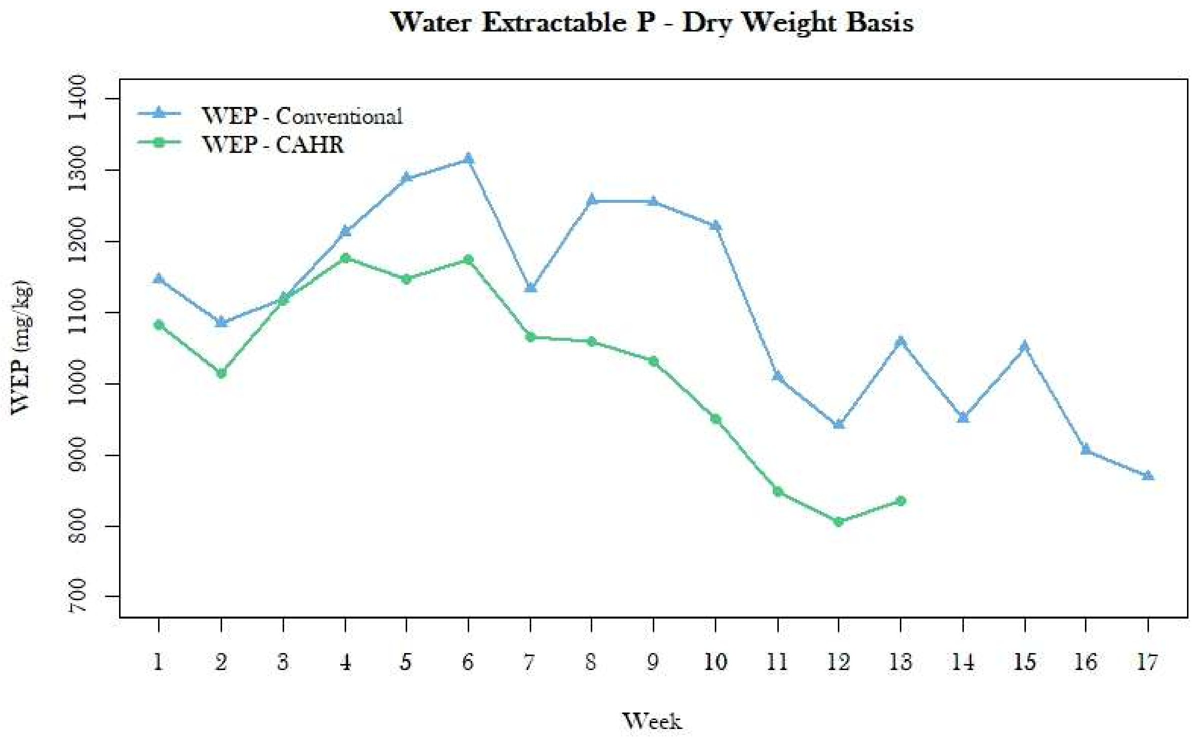


Figure 10. Water extractable phosphorus (WEP) in the conventional and CAHR compost windrows.

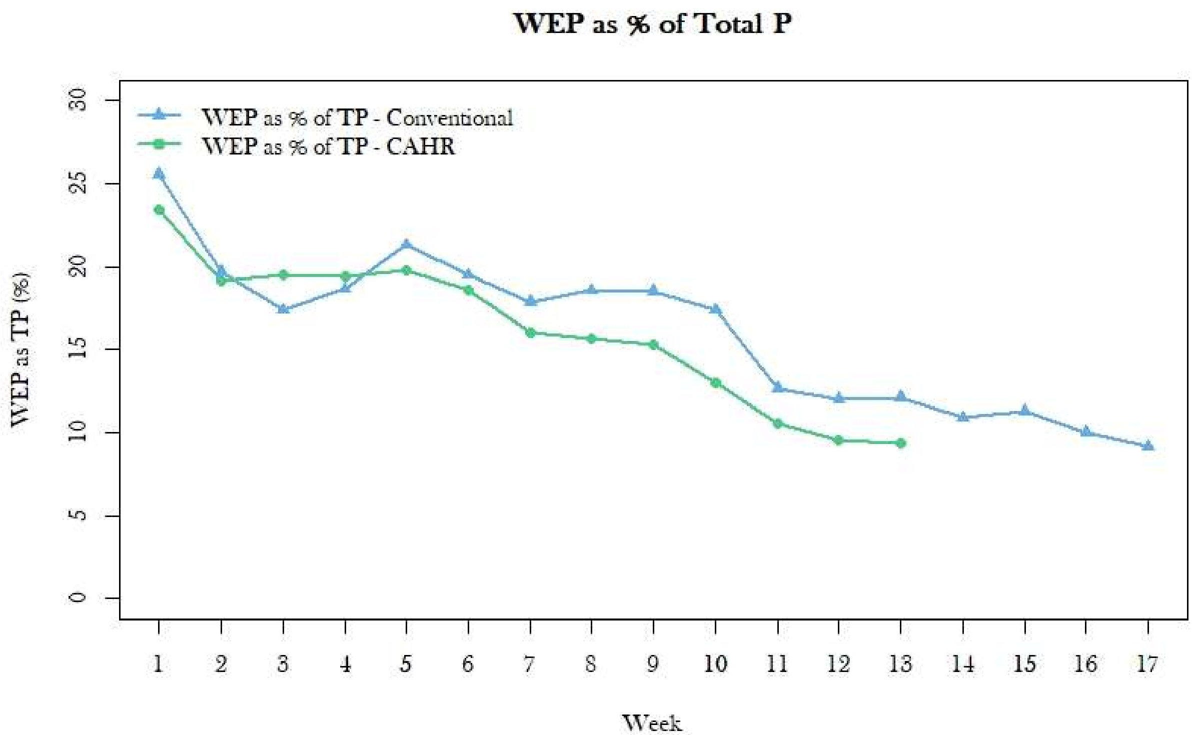


Figure 11. Water extractable P (WEP) as % of total P in the conventional and CAHR compost windrows.

2.5 POTASSIUM

Potassium (K), a vital nutrient for plants, was also analyzed in this study. As can be seen in **Figure 12**, total potassium concentration trends in both composts stayed almost identical through week 6, at which time the CAHR compost began to concentrate TK slightly more rapidly. Overall, the conventional treatment provided higher concentrations of K, likely due to the extended duration of composting.

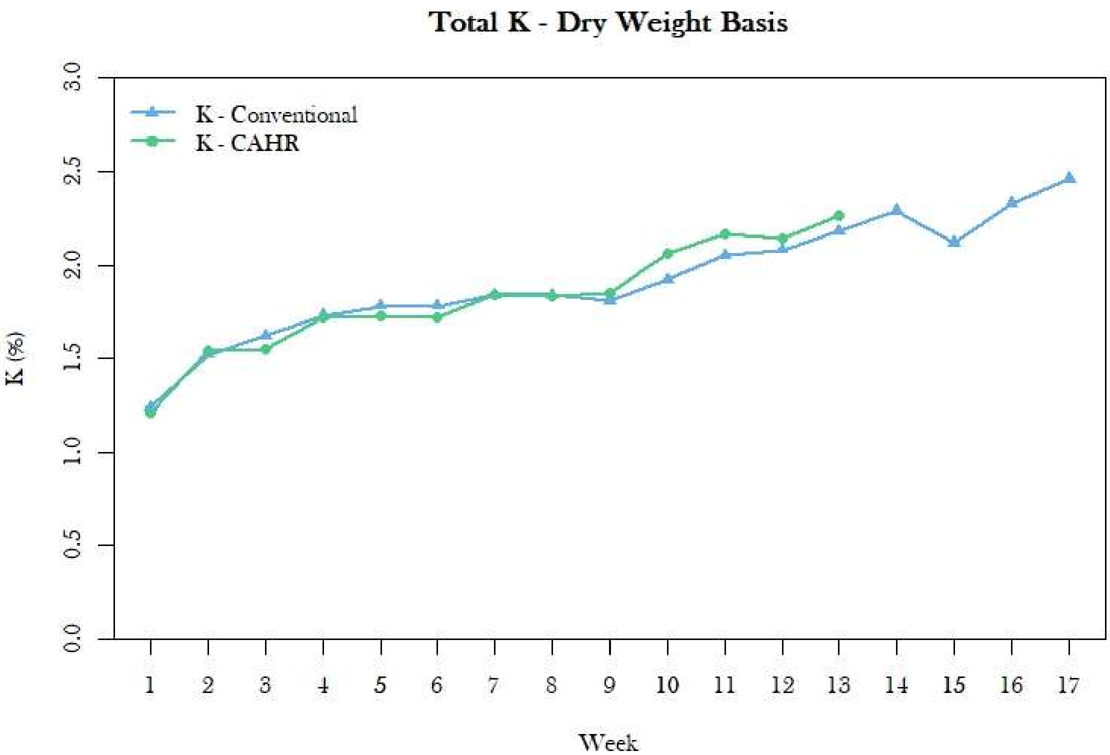


Figure 12. Potassium in the conventional and CAHR compost windrows.

2.6 PH

pH trends are shown in **Figure 13**. pH values rose in the conventional windrow through the first four weeks of the study and roughly followed CAHR trends thereafter. In the CAHR windrow, more rapid ammonia oxidation during nitrification and subsequent hydrogen ion production may have facilitated lower pH development during the first weeks of the study. In the conventional windrow, rising pH may have been an indicator for increased nitrogen loss through ammonia volatilization (Bernal et al., 2017). pH for both treatments was slightly basic throughout the process.

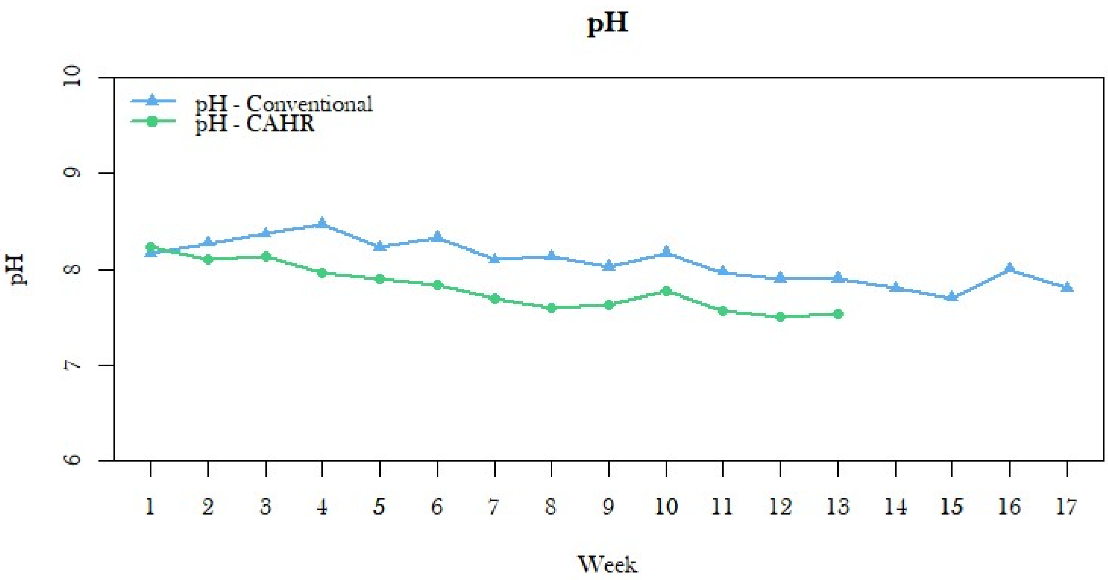


Figure 3. pH in the conventional and CAHR compost windrows.

2.7 MAJOR COMPOST TESTING METRICS: OVERALL RESULTS

Tables 1 and **2** below show the major compost testing metrics on a dry weight and as-is (wet) basis, respectively. Values included in these tables are from the initial and final sampling dates for each treatment, as opposed to the weekly averages that were presented in previous plots. These data provide a succinct method of comparing the resulting composts produced by each treatment method.

When comparing N-P-K by dry weight basis in Table 1, we see that the conventionally treated compost was slightly superior, besting the CAHR compost in N-P-K content by 2.7%, 15.9%, and 7.4%, respectively. Time must be considered when interpreting these results, and it is reasonable to conclude that the CAHR system produced a comparable product in 13 weeks, four weeks shorter than the conventional treatment's 17 weeks to maturity.

However, when comparing the primary nutrient (N-P-K) values between treatments on an as-is basis in Table 2, it is seen that the CAHR system was able to produce a nutritionally superior wet product, with respective N-P-K values 19.5%, 6.9%, and 15.3% higher than the conventionally treated counterparts.

Table 1. Dry weight basis compost test parameters, first and last days of study.

Dry Weight Basis		**TRAD**		**CAHR**	
Test Parameter	Units	Initial value on 8/24/2021	Final value on 12/15/2021	Initial value on 8/24/2021	Final value on 11/19/2021
Total N	%	1.42	2.62	1.44	2.55
Total Kjeldahl N	%	1.45	2.49	1.32	1.99
Nitrate N	%	below detection	0.13	0.12	0.56
N as NOx-N	% of TN	N/A	4.96	8.33	21.96
Phosphorus	%	0.42	1.00	0.54	0.87
WEP	mg P /kg	885	869	1083	841
P as WEP	% of TP	21	9	20	9
Potassium	%	1.18	2.46	1.25	2.29
N-P-K	%	1.42-0.42-1.18	2.62-1.00-2.46	1.44-0.54-1.25	2.55-0.87-2.29
Total Organic C	%	45.28	40.5	46.79	44.38
C:N Ratio	-	31.2	15.5	32.5	17.4
N:P Ratio	-	3.38	2.62	2.67	2.93
pH	-	8.1	7.8	8.3	7.5
Fecal Coliforms	MPN/g dry	2	10	2	4430

Fecal coliforms increased over the study, which is surprising, namely for the CAHR system, which provided higher consistent temperatures and potential for pathogen kill. Because fecal coliform data were only obtained for the first few and last samples of each treatment, we were not able to visualize trends. Increases in fecal coliform data could have arisen from a few sources, namely high bird activity at VNAP, localized high levels of coliforms that happened to be randomly sampled, and any pathogen growth between when frozen samples were shipped from UVM to when they were analyzed at A&L Labs.

Table 2. As-is compost test parameters, first and last days of study.

As-is Basis		TRAD		CAHR	
Test Parameter	Units	Initial value on 8/24/2021	Final value on 12/15/2021	Initial value on 8/24/2021	Final value on 11/19/2021
Moisture Content	%	64.73	70.53	64.22	63.85
Total N	%	0.50	0.77	0.52	0.92
Total Kjeldahl N	%	0.51	0.73	0.47	0.72
Nitrate N	%	below detection	0.04	0.05	0.20
N as NOx-N	% of TN	N/A	5.19	9.62	21.74
Phosphorus	%	0.15	0.29	0.19	0.31
WEP	mg P/kg	312	256	387	304
P as WEP	% of TP	21.16	10.34	21.05	9.68
Potassium	%	0.42	0.72	0.45	0.83
N-P-K	%	0.50-0.15 -0.42	0.77-0.29-0.72	0.52-0.19-0.45	0.92-0.31-0.83
Total Organic C	%	15.97	11.94	16.74	16.04
C:N Ratio	-	31.2	15.5	32.5	17.4
N:P Ratio	-	3.33	2.66	2.74	2.97
pH	-	8.1	7.8	8.3	7.5

2.8 MASS BALANCE ANALYSIS

A mass balance was performed for major compost nutrients, shown in **Table 3** below. Colorized columns show the nutrient retention percentages for each treatment. Interestingly, we computed values above 100% for many parameters, which would suggest nutrient input. This is unlikely, since there are no pathways for N, P, and K input from the atmosphere within the conditions of this study. Errors contributing to these calculations most likely lie in the bulk density values, as discussed in section 1.3, or in error associated with measurement of initial and final cubic yard values. Nutrient addition through watering with lagoon leachate was not considered consequential for mass balance. For example, 2.59 kg of N were added to the conventional windrow through watering, which would account for only 0.29% of the total N calculated for the finished windrow.

However, we can assess some general trends. Of N, P, and K, the only mass loss estimated (i.e., mass retention <100%) was for N in the conventional treatment. There were many pathways for nitrogen to be lost in this system but given the NOx-N dynamics discussed in section 2.2, it is likely that the conventional windrow suffered more N losses through denitrification than the CAHR windrow, with nitrate leaching and/or ammonia volatilization also possibly playing a role. The conventional windrow was also more susceptible to environmental losses due to an additional 4 weeks of composting time.

We can reason that the CAHR system had higher carbon retention due to the shorter composting duration, allowing the conventional windrow more time to continue oxidizing organic matter. This is supported by the final C:N ratio values.

Table 1. Mass balance for major compost nutrients.

Mass Balance		**TRAD**			**CAHR**		
Test Parameter	Units	Initial value on 8/24/2021	Final value on 12/15/2021	**Retention (%)**	Initial value on 8/24/2021	Final value on 11/19/2021	**Retention (%)**
Bulk Density	lb/CY	910	1106	N/A	869	967	N/A
Windrow Volume	CY	480	234	**49**	549	320	**58**
Nitrogen	kg	991	903	**91**	1125	1291	**115**
Phosphorus	kg	297	340	**114**	411	435	**106**
Potassium	kg	833	845	**101**	973	1165	**120**
Total Organic Carbon	kg	31665	14009	**44**	36206	22514	**62**

3. **COST AND CONSUMABLES ANALYSIS**

In addition to laboratory testing and analyses of nutrient content, a cost and consumables analysis was performed to compare operational and energy costs between the CAHR and conventional treatments. Results of this analysis are provided in **Table 4**, with the following operational activities and assumptions considered:

- Compost turning with the Komptech Topturn x53 straddle turner
  - 10 L/hr fuel use during turning, provided by VNAP
  - 6.5 minutes to turn a 200’ windrow, provided by VNAP
  - $60/hr operator wage, provided by VNAP
  - 9 turning events for the conventional windrow
  - 8 turning events for the CAHR windrow
- Compost watering with a 4400-gallon liquid manure tanker
  - 5L/hr fuel use during watering, estimated as half of turner fuel use rate
  - 20 minutes to fill and dispense 4400 gallons of liquid leachate, timed by FB
  - $60/hr operator wage, provided by VNAP

    - 1 watering event of 4400 gallons for the conventional windrow
    - 2 watering events of 4400 gallons for the CAHR windrow
- Aeration by the CAHR system
    - 746-watt (1 hp) power draw by the aeration fan, provided by Agrilab Technologies
    - 12 hours of aeration for the CAHR test window/day
    - 88 days of aeration for the CAHR test windrow
    - 17.33 cents/kWh average commercial electric rate in VT, provided by US EIA

Table 2. Operational financial and energy costs in the conventional and CAHR composting systems.

	TRAD		CAHR	
CY finished compost	234		320	
Operational Activity	Financial cost ($)	Energy Cost (kWh)	Financial cost ($)	Energy Cost (kWh)
Compost Turning	$ 58.50	103.71	$ 52.00	92.18
Compost Watering	$ 20.00	17.73	$ 40.00	35.46
Aeration Blower Fan	$ -	0.00	$ 136.52	787.78
Total	**$ 78.50**	**121.44**	**$ 228.52**	**915.42**
Total (per CY finished compost)	**$ 0.34**	**0.52**	**$ 0.71**	**2.86**

See Attachment B for detailed cost and consumables calculations

From both an energy and financial cost standpoint, this analysis suggests that the conventional management of composts is less expensive than using the CAHR system. Important to note is that these calculations *only* account for normal operational inputs from the time compost batches were assembled until they were removed from production. This study does not account for any time and space savings provided by a managed aeration system and does not include the energy and cost savings benefits of the CAHR system to an agricultural producer or waste manager, which have been well documented at VNAP and are summarized in **Table 5** below (Foster et al., 2018).

Table 5. Cost savings per cubic yard of finished compost for the CAHR composting system relative to the conventional system.

Cost Savings Parameter	CAHR
Operational cost savings	$ (0.37)
Energy/Heating cost savings (Foster, et al., 2018)	$ 2.05
Avoided infrastructure cost savings (Foster, et al., 2018)	$ 2.38
Total savings (per CY finished compost)	**$ 4.06**

Considered in the energy and heating cost savings are the reduced demand for #2 heating oil used to heat the VNAP bagging building and propane used to dry composts prior to bagging. Heat captured from composts by the CAHR system reduces demand for these two fuel sources. The avoided infrastructure cost savings approximate projected expansion expenses that VNAP avoids through adoption of the CAHR system. If the CAHR system were not implemented, the facility would need to be expanded, as a greater pad area and lagoon volume are required to process traditionally turned windrows while still meeting annual product demand. Be mindful that these cost savings estimates are based on 2018 unit prices for #2 heating oil, propane, permitting, and earthwork, among others.

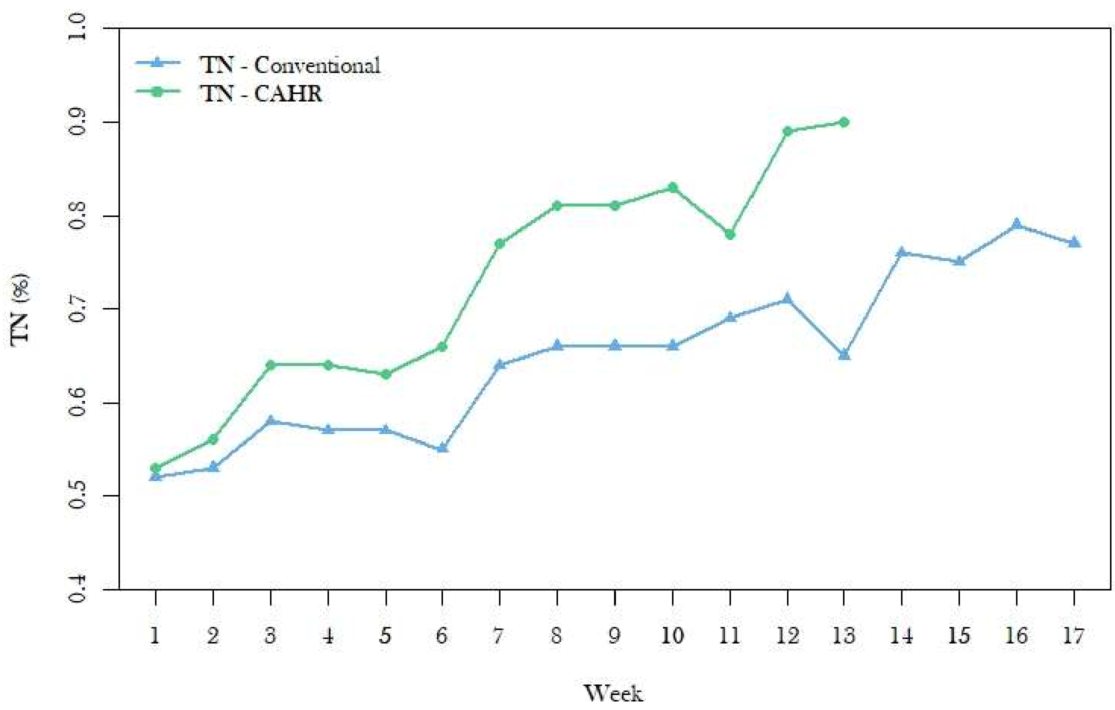
4. CONCLUSIONS

This study evaluated nutrient status, financial cost, and energy cost for a pair of commercial compost windrows in a normal production setting. From a time and space management standpoint, compost treated with a forced-aeration system was deemed suitable for market in approximately 75% of the time as a conventionally turned windrow; 13 and 17 weeks, respectively. Analysis of nitrogen species status throughout the study suggests that greater nitrogen losses occurred during conventional treatment than during CAHR treatment, presumably due to higher rates of denitrification and ammonia volatilization. Data also suggest a lower risk for phosphorus loss through leaching from CAHR-treated compost, as WEP concentrations were consistently higher in the conventional treatment. During the active composting process, it was found that operational costs for CAHR compost were 2.1 times more expensive financially and 5.5 times more energy-intensive than a conventional compost on a per CY basis. However, the energy and infrastructure cost offsets provided by the CAHR system (as operated at VNAP) could provide a net savings of $4.06/CY finished compost. In this study, it was shown that a CAHR system produced a comparable compost product, with higher operational input, in less time.

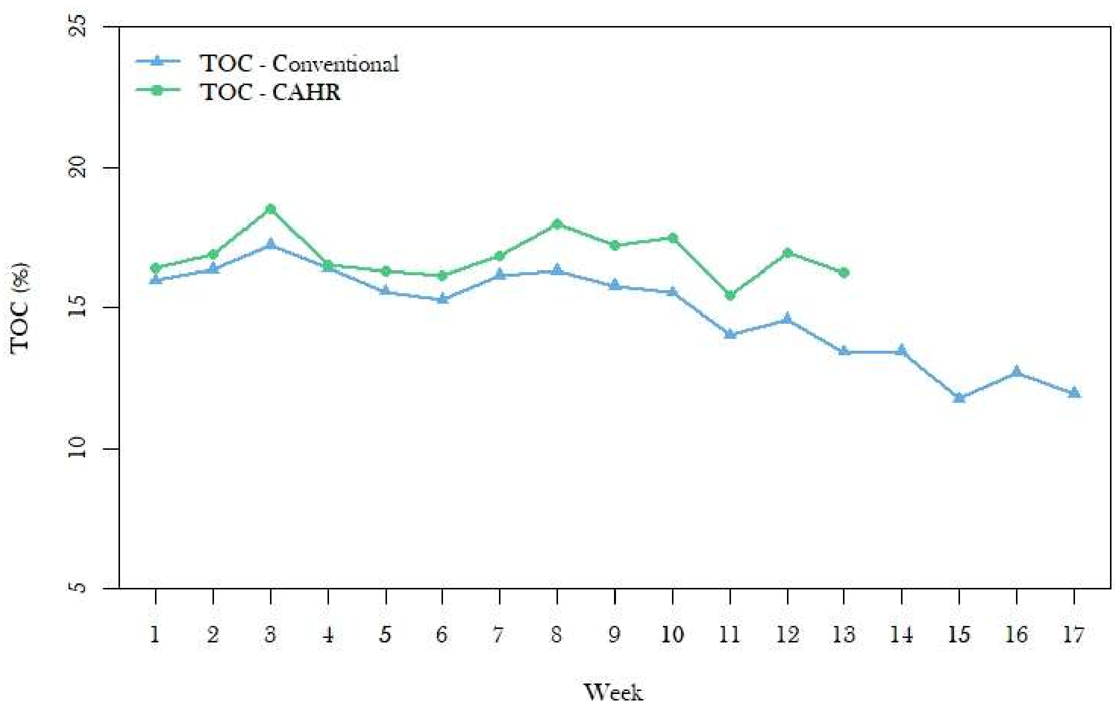
Furthermore, the data suggest that land application of either compost treatment evaluated in this study may reduce phosphorus loss due to leaching versus direct manure application. For example, WEP concentrations in the finished composts in this study ranged between 0.256 and 0.304 g/kg on a dry weight basis, while WEP concentrations in dairy manures have been found to range between 1.98 and 4.0 g/kg (P. Kleinman et al., 2007; P. J. A. Kleinman et al., 2005). It is probable that either compost treatment, when applied to agricultural land, would release less phosphorus as WEP during rainfall events than direct manure application, providing water quality benefits.

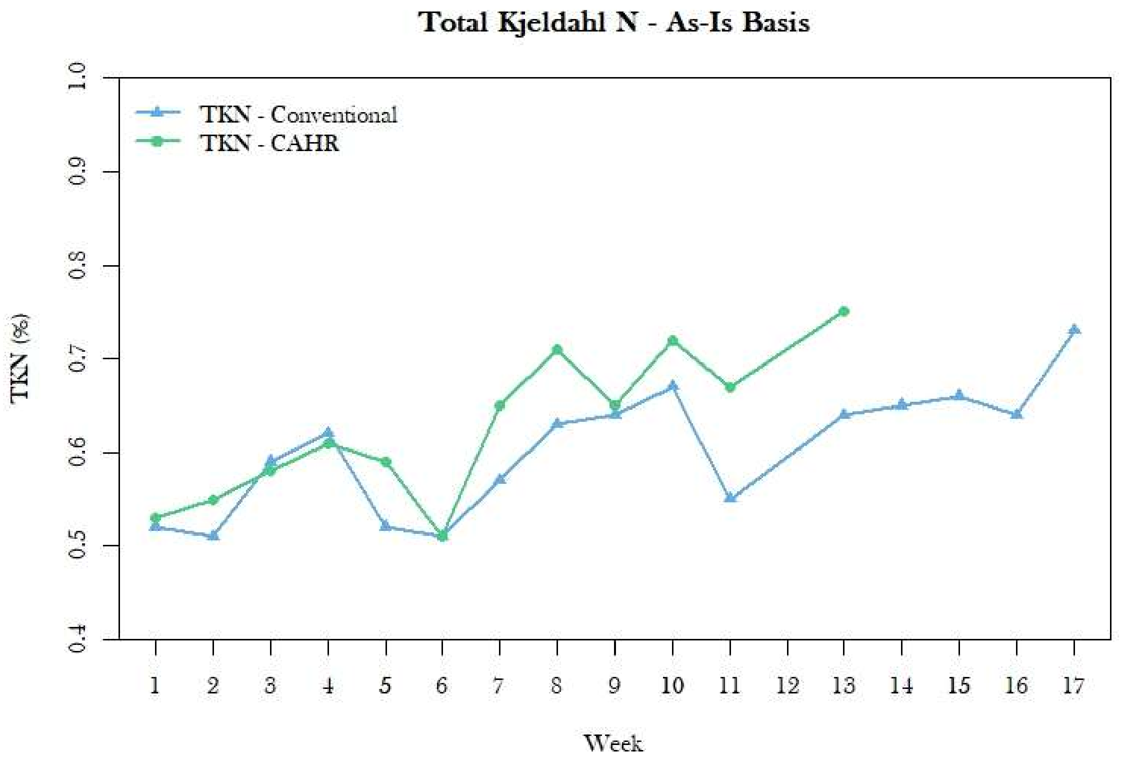
ATTACHMENT A: NUTRIENT DYNAMICS PLOTS BY "AS-IS", OR WET, BASIS

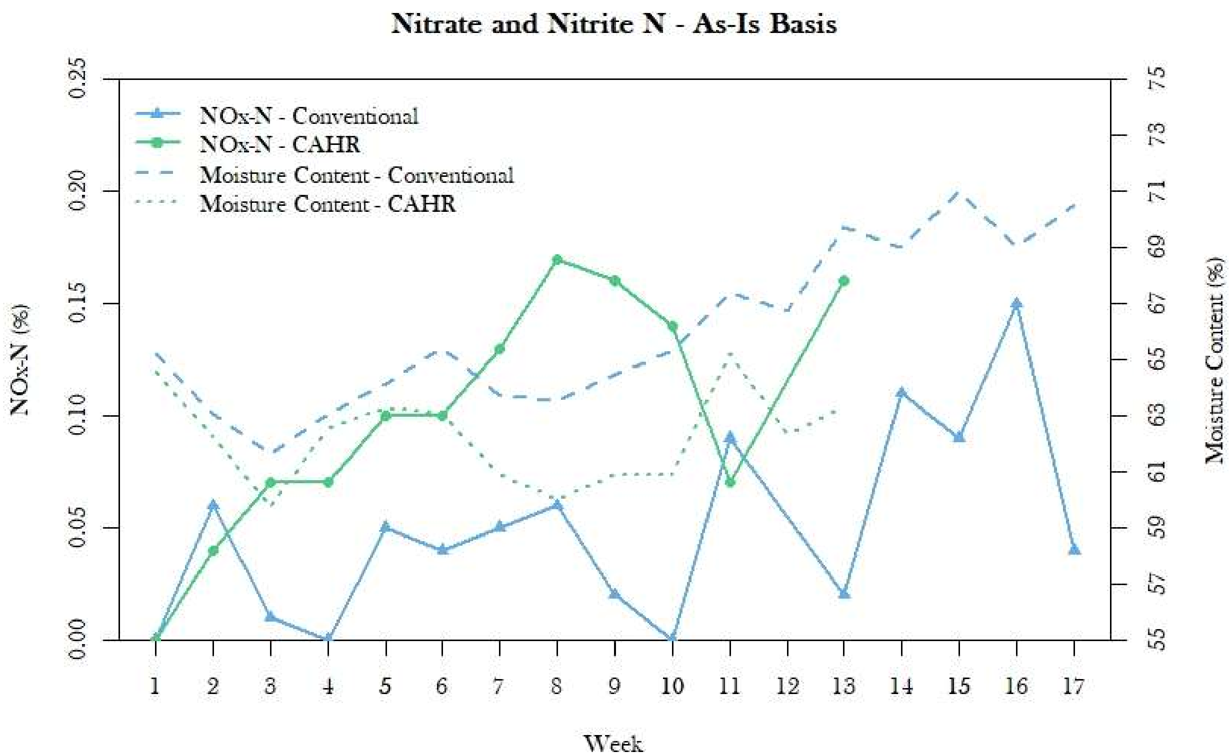
Total N - As-Is Basis



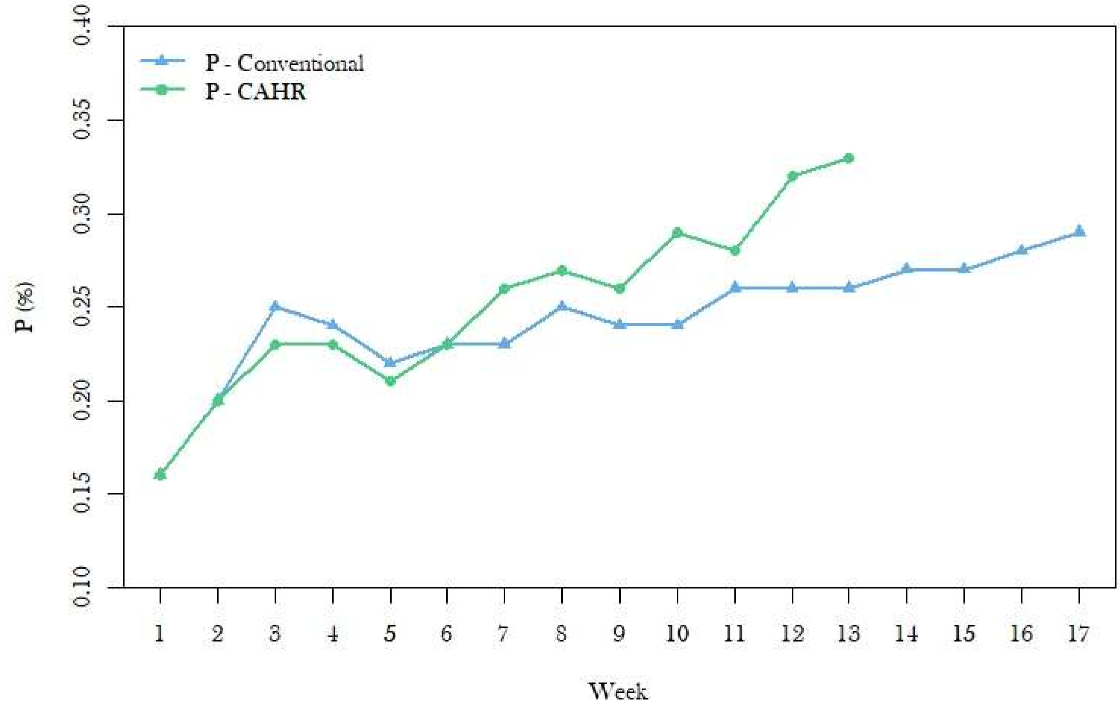
Total Organic Carbon - As-Is Basis



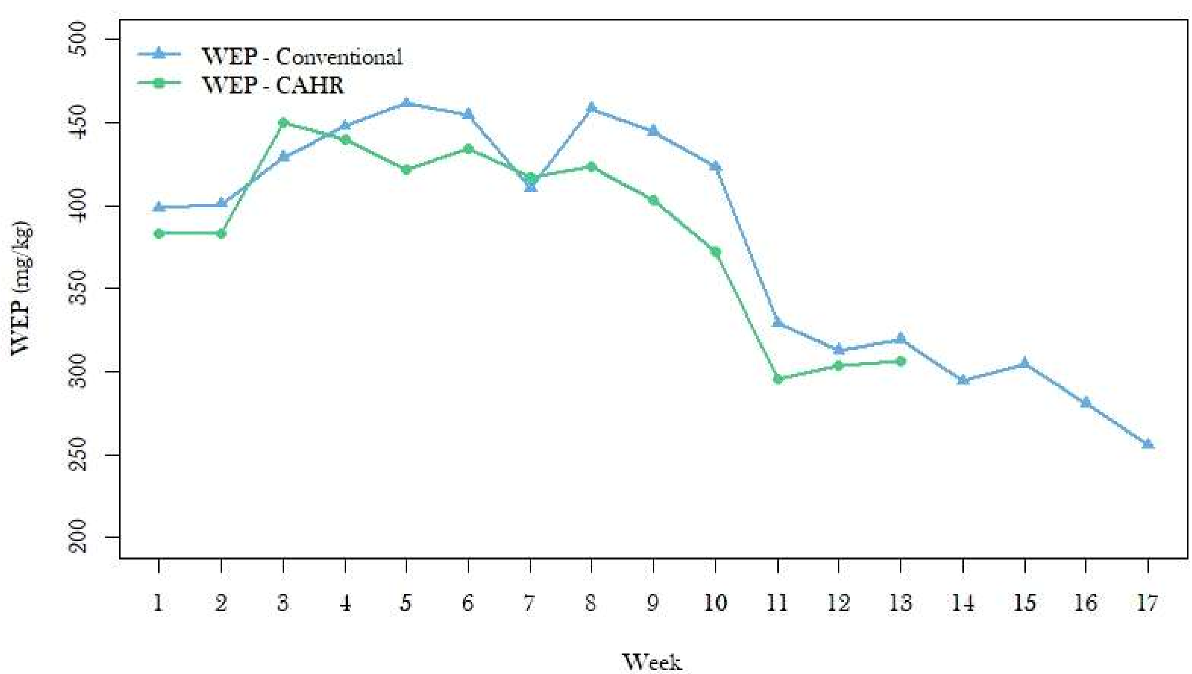

Total Kjeldahl N - As-Is Basis
TKN - Conventional
TKN - CAHR
TKN (%)
Week

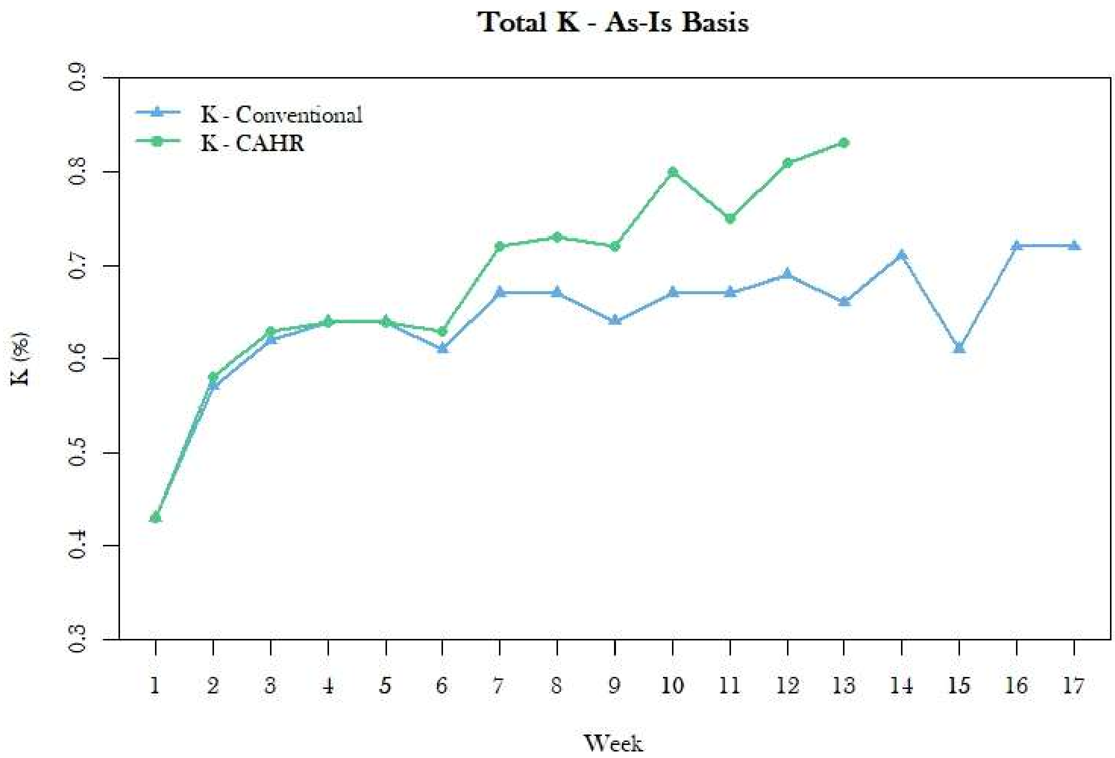

Nitrate and Nitrite N - As-Is Basis
NOx-N - Conventional
NOx-N - CAHR
Moisture Content - Conventional
Moisture Content - CAHR
NOx-N (%)
Moisture Content (%)
Week

Total P - As-Is Basis



Water Extractable P - As-Is Basis




Total K - As-Is Basis
K - Conventional
K - CAHR
K (%)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Week

ATTACHMENT B: COST AND CONSUMABLES CALCULATIONS

	TRAD		CAHR	
CY finished compost	234		320	
Operational Activity	Financial cost ($)	Energy Cost (kWh)	Financial cost ($)	Energy Cost (kWh)
Compost Turning	$ 58.50	103.71	$ 52.00	92.18
Compost Watering	$ 20.00	17.73	$ 40.00	35.46
Aeration Blower Fan	$ -	0.00	$ 136.52	787.78
Total	**$ 78.50**	**121.44**	**$ 228.52**	**915.42**
Total (per CY finished compost)	**$ 0.34**	**0.52**	**$ 0.71**	**2.86**

Conversion Factors	
Liters/ gallon	3.7854
BTU/gallon	137381
kWh/BTU	3412

	Compost Turning - Financial Costs			
	Turning events (ea)	Time/turn (hr/event)	Operator rate ($/hr)	Total Cost ($)
TRAD	9	0.108	$ 60.00	$ 58.50
CAHR	8	0.108	$ 60.00	$ 52.00

	Compost Turning - Energy Costs			
	Turning events (ea)	Time/turn (hr/event)	Fuel use rate (L/hr)	Total Cost (kWh)
TRAD	9	0.108	10	103.71
CAHR	8	0.108	10	92.18

	Compost Watering - Financial Costs			
	Watering events (ea)	Time/water (hr/event)	Operator rate ($/hr)	Total Cost ($)
TRAD	1	0.33	$ 60.00	$ 20.00
CAHR	2	0.33	$ 60.00	$ 40.00

	Compost Watering - Energy Costs			
	Watering events (ea)	Time/water (hr/event)	Fuel use rate (L/hr)	Total Cost (kWh)
TRAD	1	0.333	5	17.73
CAHR	2	0.333	5	35.46

	Aeration Blower Fan - Financial Costs				
	Estimated power draw (kW)	Hours run/day for study windrow	Days of study	Cost/kWh ($)	Total Cost ($)
TRAD	0	0	114	$ 0.17	$ -
CAHR	0.746	12	88	$ 0.17	$ 136.52

	Aeration Blower Fan - Financial Costs			
	Estimated power draw (kW)	Hours run/day for study windrow	Days of study	Total Cost (kWh)
TRAD	0	0	114	0.00
CAHR	0.746	12	88	787.78

ATTACHMENT C: VNAP LAGOON LEACHATE NUTRIENT REPORT

Report Number
F21259-6510
Account Number
63570

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Scientists who don't mind getting dirty.™

3505 Conestoga Dr.
Fort Wayne, IN 46808
260.483.4759
algreatlakes.com

To: NEWTRIENT LLC
11510 LAURIE DR
WHEATFIELD, IN 46392-7364

For: UNIVERSITY OF VERMONT
ROY LAB

Attn: MARK STOERMAN

Lab Number: 38250
Sample ID: VNAP LAGOON 9/8/21 FAB
Manure Type: DAIRY, LAGOON (21)

Date Sampled: 9/8/2021
Date Received: 9/16/2021
Date Reported: 9/21/2021 Page: 1 of 1

MANURE ANALYSIS

Analysis	Unit	Analysis Result (As Received)	Pounds Per 1,000 Gal**	First Year Availability @ Pounds Per 1,000 Gal
Moisture	%	99.88	8320	
Solids	%	0.12	10	
Nitrogen, Total Kjeldahl (TKN)	%	0.016	1.3	0.9 *
Nitrogen, Ammonium (NH_4-N)	%	0.000	0.7	0.7 *
Nitrogen, Organic (N)	%	0.008	0.7	0.2 *
Phosphorus (P)	%	0.001	0.2 (as P_2O_5)	0.2 * (as P_2O_5)
Potassium (K)	%	0.028	2.8 (as K_2O)	2.8 * (as K_2O)

@ Estimate of first-year availability does not account for incorporation losses. Consult MWPS-18, "Livestock Waste Facilities Handbook" for additional information.
* Source: MWPS-18, Livestock Waste Facilities Handbook, 1993 # Source: A3411, "Manure Nutrient Credit Worksheet", University of Wisconsin
** Manure density assumed to be 8.33 lb/gallon

Report Approved By: [signature] Approval Date: 9/21/2021

Don Burgess - Agronomist / Technical Services - CPAg/CPSS/CCA

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