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Research Case Study

Performance of a Compost Aeration and Heat Recovery System at a Commercial Composting Facility

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Composting of agricultural and forestry residuals can support regional nutrient management and environmental goals but faces various operational challenges. This case study evaluated nutrient status and financial and energy cost for a pair of commercial compost windrows with and without forced aeration at full scale in a normal production setting. Compost treated with a forced aeration and heat capture system was deemed suitable for market in approximately 25% less time than a conventional, straddle-turned windrow. Analysis of nitrogen (N) dynamics throughout the study suggested that forced aeration promoted N retention. From a mass balance analysis, force-aerated compost retained ~23% more of its initial total N (TN) by mass as compared to conventionally treated compost, which we hypothesize was due to greater rates of N losses to the atmosphere in conventional treatment. Consistently lower water-extractable phosphorus (WEP) suggested a lower risk for phosphorus (P) loss through leaching from force-aerated composting. During the active composting process, operation of force-aerated composting was 2.1 times more expensive and 5.5 times more energy-intensive than a conventional compost per m^3. However, the energy and infrastructure cost offsets provided by the aeration and heat capture system as operated by this commercial compost facility could provide a net savings of $1.51 per m^3 finished compost when analyzed over the lifetime of the system's construction, operation, and use. This case study illustrates that forced aeration and heat capture systems have potential to provide time and energy savings benefits to compost producers, while maintaining or enhancing nutrient retention and compost quality.

Keywords Bioenergy; Forced aeration; Manure; Nutrient management; Organic wastes

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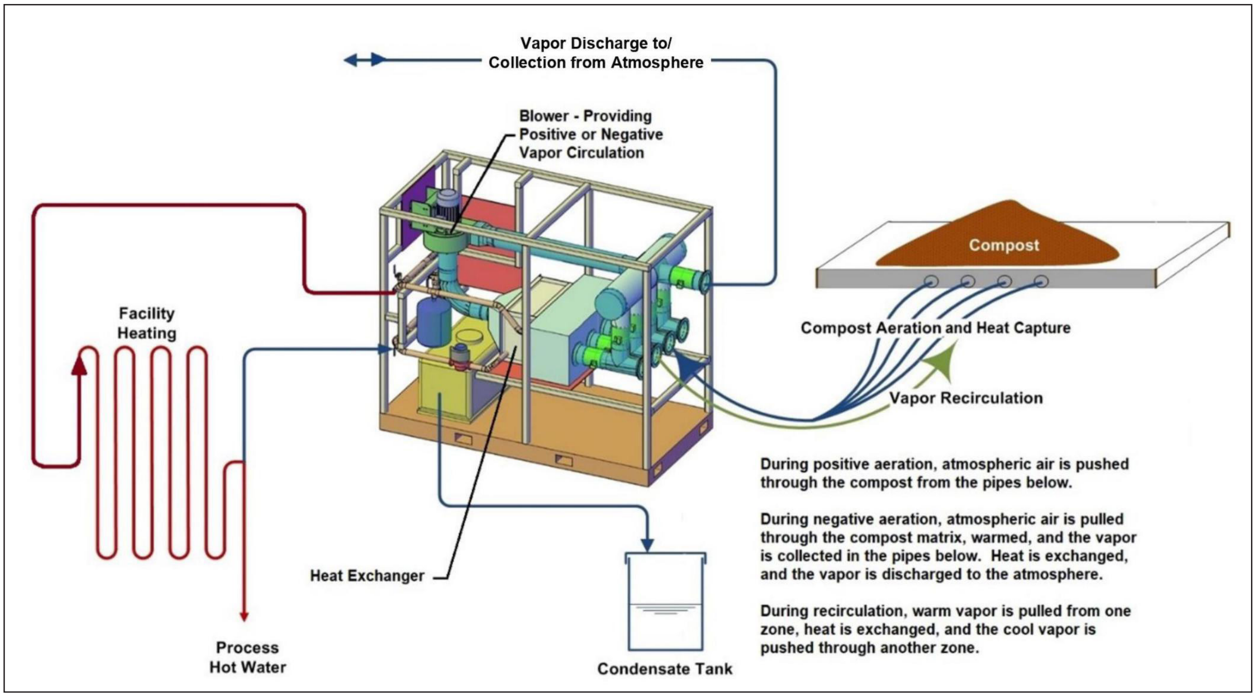

Graphical Abstract: Compost aeration and heat recovery (CAHR) system (adapted with permission from Agrilab Technologies Inc. [2021])

Highlight

A forced aeration and heat capture system installed at a commercial composting facility was found to reduce the time needed to produce marketable compost by approximately 25% and provide cost savings of \$1.51/m^3 to the compost producer through offsetting energy and facility expansion costs. The system also reduces the possibility of nutrient losses to the environment through a 5 times greater NO_x-N retention efficiency and a reduction of water-extractable P by 11.5%.

1. Introduction

Composting is an aerobic process governed by ecological functions that has been employed for centuries to add value and stability to a variety of organic residuals, including manure. During composting, microbial and fungal communities transform organic residuals into humus-like material containing nutrients and organisms that enhance plant growth while respiring some of the feedstock carbon as carbon dioxide (CO_2) to the atmosphere (Bernal et al. 2017; de Bertoldi et al. 1983; Goyal et al. 2005; Onwosi et al. 2017). Organic residuals such as manure, crop and forest biomass, food scraps, and straw are generally heavy and high-volume, and composting is seen as a suitable method to increase their suitability for transport and enhance their value as soil additives (Jäckel et al. 2005).

Composting a variety of feedstocks can serve local and regional nutrient management needs, integrating the agricultural, food waste diversion, and forestry sectors, among others, and support efforts to develop a sustainable circular bioeconomy (Bernal et al. 2017; Roy et al. 2021; Tully and Ryals 2017). Within the agricultural sector alone, compost producers can source feedstocks such as anaerobic digestate, animal bedding, plant wastes, and manures (Barampouti et al. 2020; Guo et al. 2012; Onwosi et al. 2017), helping to meet nutrient cycling needs, especially if finished composts are redistributed to nutrient deficient locations within the region (Powers et al. 2019).

One key benefit of composting is that it is an exothermic process; microbial colonies release heat while metabolizing organic matter (Bernal et al. 2017). Due in large part to heat generation, the composting process is used to remove pathogens and kill weed seeds in organic residuals, creating a finished product rich in organic matter and plant nutrients and suitable for agricultural application (Onwosi et al. 2017). However, compost generation is not without challenges and is a time- and space-intensive process (Bernal et al. 2017).

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If not conducted properly, composting can result in nutrient loss through leaching and volatilization (Yang et al. 2019) and excess greenhouse gas (GHG) emissions (Bernal et al. 2017; Hao et al. 2002; Jiang et al. 2013).

Composts are typically aerated in one of 3 ways: physical turning, passive aeration, or forced aeration (Chowdhury et al. 2014). In physical turning, compost windrows or piles are turned regularly to mix the material and reinvigorate microbes by supplying oxygen (O_2) (Solano et al. 2001). In passive aeration, perforated pipes or tubes are placed underneath or within the compost, allowing air and compost vapor to flow passively through the pile (Ogunwande and Osunade 2011). In forced aeration, perforated pipes or tubes are placed underneath or within the compost, and air and compost vapor are pushed into and/or out of the pile, typically with electric pumps or fans (Puyuelo et al. 2014; Zhang Z et al. 2021). Providing aeration during composting has been shown to reduce harmful GHG emissions (Jiang et al. 2013; Ma et al. 2020), namely nitrous oxide (N_2O) and methane (CH_4), through the reduction of anaerobic zones, and to promote humification of organic material (Zhang S et al. 2021; Zhang Z et al. 2021).

Although exothermic, composting is not widely regarded as an energy source and the heat generated is typically lost to the atmosphere (Smith et al. 2017). For commercial compost producers, capturing the heat generated during composting could serve as a viable energy source to offset the fuel requirements of heating buildings and water, or to support various system processes such as drying or cold season plant growth. Heat can be recovered from compost in 3 ways: directly, by conduction, or by vapor heat exchange (Smith et al. 2017). Direct heat recovery typically situates the compost inside a greenhouse or underneath growing plant beds. Conductive heat recovery typically passes water or other liquid through piping embedded within the compost volume, allowing the compost to heat the liquid. Vapor heat exchange captures the warm vapor within the pore space of the compost and passes this vapor through a heat exchanger to heat water or other liquid (Smith et al. 2017).

In a review of compost heat recovery systems by Smith et al. (2017), results from lab, pilot, and commercial-scale studies were compared. Heat recovery ranged from 1159 kJ/kg dry matter (DM) to 7084 kJ/kg DM and was dependent on multiple factors, including system scale, type, configuration, and operation. Various commercial-scale aeration and heat capture technologies are emerging (e.g., Agrilab Technologies Inc. 2022) that have potential to ease budgetary pressure and reduce time and space requirements (Smith et al. 2017). Currently, systems are available for facilities that manage their composts either as aerated static piles (ASP) or turned aerated piles (TAP). In ASP systems, a mass of compost sits statically in a large pile or in a bin over a network of perforated piping and is turned infrequently (Michel et al. 2021). In TAP composting, stand-alone piles or windrows dimensioned to be turned periodically with a straddle turner (a machine with a rotating drum that mixes compost as it is driven down the windrow) are underlain with perforated piping to capture compost vapor (Michel et al. 2021).

There is a small body of literature on heat capture from compost (Bajko et al. 2019; Malesani et al. 2021; Mwape et al. 2020; Smith and Aber 2018), and a wider body of literature addressing the benefits of aerating compost (Chowdhury et al. 2014; Guo et al. 2012; Park et al. 2011; Yang et al. 2019; Zhang Z et al. 2021). Yet, an analysis of compost nutrient dynamics at a commercial-scale facility using a heat capture system to provide forced aeration has not been undertaken to our knowledge. Thus, a gap in understanding exists regarding compost nutrient status and economics of heat capture systems at commercial scales. Filling this knowledge gap could help practitioners make more informed decisions about the feasibility, design, and management factors involved in implementing heat capture systems at their facilities.

The objective of this case study was to evaluate nutrient dynamics and operational costs within a compost aeration and heat recovery system (CAHR) at a commercial compost facility in Vermont, United States, in comparison to conventional windrow composting in which aeration only occurs via periodic physical turning. We hypothesized that a heat capture system may help serve 2 goals: compost nutrient retention and cost savings. To test our hypothesis quantitatively, we measured the overall compost maturation timeline and several metrics that collectively approximate nitrogen (N) and phosphorus (P) contents and risk of loss through time. We also analyzed cost and energy use data for each system.

Although the formal definition of ecological engineering can vary (Mitsch and Jørgensen 2003; Schönborn and Junge 2021), the underlying goal does not: the integration of ecology and engineering to provide solutions that benefit humans and their environment. This case study is exemplary of ecological engineering in 3 ways. First, the CAHR system studied combines biological processes driven by microbial communities influencing ecosystem function with non-biological technology and human management. Second, the potential for the CAHR system to reduce environmental impacts (e.g., nutrient emissions to the environment) and provide human benefits (e.g., building heating) was a focus of the case study. Finally, one aim of this work was to produce knowledge that can help increase the viability of a regional circular bioeconomy inspired by ecology.

2. Materials and Methods

The protocol for this study was adapted from "Protocol for Third Party Evaluation of Agricultural Nutrient Management Technologies" (Bronstad et al. 2019). The evaluation protocol by Bronstad et al. is written to assess the management of liquid manures. The protocol herein has been adapted to assess the management of solid materials.

2.1 Study Site

This study was undertaken at the Vermont Natural Ag Products (VNAP) composting facility in Middlebury, Vermont, United States. VNAP produces compost in batched windrows, with feedstocks sourced regionally from livestock producers, forest products processors, agricultural fairs, and food waste diversion programs. The typical aeration method used by VNAP is through periodic physical turning with a straddle turner. Of the approximately 2.6 ha of the VNAP facility dedicated to windrow composting, only 0.3 ha is managed through forced aeration with a CAHR system designed by Agrilab Technologies Inc. To provide adequate mixing and to avoid preferential vapor flow paths, the CAHR-treated windrows are also turned periodically.

The design of the TAP CAHR system operated at VNAP includes compost windrows placed on a paved pad containing a shallow trench oriented longitudinally with the windrow. The trench contains perforated high-density polyethylene piping bedded in wood chips. These pipes are connected to solid, insulated plastic piping that runs to a shipping container equipped with a control panel, circulation fans, and a heat exchanger. When 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 is used to heat the facility's compost packaging building via radiant floor heating and to dry finished compost prior to screening and bagging. The CAHR system is set up with 4 zones of perforated piping, each of which is operated 25% of the time by the circulation fans. At a given time, one of 3 scenarios is typically taking place:

Scenario 1: Vapor is pulled from one zone, run through the heat exchanger, and exhausted to the environment (negative aeration).

Scenario 2: Fresh air is pulled from the environment, heated, and used to positively aerate one zone for product drying purposes.

Study Photograph. The compost aeration and heat recovery system at Vermont Natural Ag Products (photo: Finn Bondeson)

Scenario 3: Vapor is pulled from one zone, run through the heat exchanger, and pushed into another zone.

Due to elevated O_2 levels provided by positive and negative aeration, CAHR-treated compost has been reported by VNAP to mature more quickly and require less turning, reducing diesel, labor, and equipment maintenance costs (Foster et al. 2018).

2.2 Study Treatments

Two compost windrows of equivalent feedstock contents and ratios were monitored. The control, denoted as "conventional", was a conventionally treated windrow that did not receive aeration aside from periodic windrow turning with a Komptech Topturn x53 compost turner (Frohnleiten, Austria, and Denver, Colorado, United States). The experimental windrow, denoted as "CAHR", received periodic positive and negative aeration via the CAHR system, as well as aeration through periodic turning. Both windrows were turned successively on the same day, on a 1- to 2-week interval. The conventional windrow was turned 9 times and the CAHR windrow was turned 8 times. The initial volumes of the conventional and CAHR windrows were 367.1 m^3 and 419.6 m^3, respectively.

The initial feedstock composition of both windrows was as follows, by volume:

- Sawdust: 47%
- Dairy manure: 23%
- Dairy bedding: 23%
- Chicken manure: 6%
- Wood ash: 1%

Additional information about compost management by VNAP staff is given in the Supplementary Material, Text S2.

2.3 Sampling and In-Situ Data Collection

Compost samples were collected between August 24, 2021, and December 15, 2021. For the first 13 weeks of the sampling period, samples were taken 3 times weekly from both treatments. At the end of week 13, on November 19, 2021, VNAP staff deemed the CAHR treatment compost suitable for market and it was pulled for processing. Sampling continued once weekly for the conventional treatment for 4 weeks, terminating on December 15, 2021, when the conventional windrow was pulled for processing. This resulted in 43 samples of conventional compost and 39 samples of CAHR compost.

To determine sampling points, a coordinate system (x,y,z) 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 an 18.9 L sample was taken from each sample point with a steel spade and bucket. For each treatment, samples were composited on a plastic sheet and mixed vigorously, resulting in 151.4 L of composited sample. From each composite, a 7.6 L sub-sample was collected and kept frozen prior to analysis, and a 1 L sub-sample was collected and kept refrigerated prior to analysis.

At each sample point, a 0.9 m probe REOTEMP Heavy Duty Compost Dial Thermometer with 2 °F minor and 10 °F major graduations and 0 °F to 200 °F range (accuracy ±1% of scale) was used to gather manual temperature data. For the conventional treatment, it was observed that temperature stratification was occurring within the windrow, likely due to varied O_2 levels at different depths from the windrow surface. Therefore, one temperature reading was taken at approximately 0.2 m to 0.3 m from the surface, where temperatures were higher, and one temperature reading was taken at the full 0.9 m depth. These 2 temperatures were averaged for each sample point to represent windrow temperature more accurately. For the CAHR treatment, temperature stratification was not observed, and a single temperature reading was recorded at 0.9 m depth at each sample point.

An in-situ bulk density estimate was taken weekly for each of the 18.9 L samples taken. Bulk density was established using the "partial fill and drop" method (Breitenbeck and Schellinger 2004). Information regarding atmospheric data collection at VNAP during the study period is given in the Supplementary Material, Text S3.

2.4 Sample Analysis

Frozen samples were sent to A&L Great Lakes Laboratories (A&L) in Fort Wayne, Indiana, United States, 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 metrics used in this study: solids/moisture content, total organic carbon (TOC), carbon to nitrogen (C:N) ratio, total nitrogen (TN), total phosphorus (TP), potassium (K), pH, germination, respiration, and fecal coliforms. All other samples were tested for constituents in A&L's C6 testing package, which includes the following metrics used in this study: solids/moisture content, TOC, C:N ratio, TN, P, K, and pH (A&L 2022). For each treatment, total Kjeldahl nitrogen (TKN) was also analyzed at the 3 sampling instances during week 1, then once weekly through the remainder of the study. NO_x-N (the sum of nitrate N [NO_3-N] and nitrite N [NO_2-N]) was calculated by subtracting TKN from TN. Due to the once-weekly sampling resolution, statistical comparisons between treatments for TKN and NO_x-N were conducted on a monthly basis. All testing performed by A&L followed procedures outlined in the US Composting Council's Test Methods for the Examination of Composting and Compost (US Composting Council 2002).

To quantify the NO_x-N dynamics shown in Figure 3c, the cumulative observed NO_x-N produced and lost (through week 13) was summed for each windrow on a g/kg basis, and the percent of observed NO_x-N retained was computed for each windrow using the following formula:

$$\%\,NOx\ retained = \frac{(\Sigma\ NOx\text{-}N\ produced - \Sigma\ NOx\text{-}N\ lost)\ (g/kg)}{\Sigma\ NOx\text{-}N\ produced\ (g/kg)} \times 100 \qquad (1)$$

All refrigerated samples were held for no longer than 72 h before analysis for water-extractable phosphorus (WEP). WEP is the portion of TP most available to plants but also susceptible to leaching loss, and thereby proxies the only way for P to be lost from these composts (Kleinman et al. 2007). This analysis was performed at the University of Vermont following Kleinman et al. (2007). In summary, 10 g to 15 g of each sample were weighed in triplicate and dried at 60 °C for 18 h 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 1 h 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 and Jarrell 1999).

2.5 Nutrient Mass Balance Approximations

At the beginning and end of the study, nutrient content, density, and volume measurements were taken, and the following equation was used to approximate total N, P, K, and C masses contained in each treatment:

$$Nutrient\ mass\ (kg) = Nutrient\ content\ \left(\frac{kg}{kg}\right) \times Compost\ density\ \left(\frac{kg}{m^3}\right) \times Windrow\ volume\ (m^3) \quad (2)$$

Nutrient contents used in Equation 2 were "as is" values (i.e., mass nutrients per wet-basis mass of compost). Compost bulk density in Equation 2 was also on a wet weight (i.e., "as is") basis.

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

$$\%\ Nutrient\ retention = \frac{Nutrient\ mass\ (final)}{Nutrient\ mass\ (initial)} \times 100 \quad (3)$$

It should be noted that because the 18.9 L 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, reducing the precision of the results but maintaining the relative differences between the treatments.

2.6 Energy and Expense Monitoring

Data quantifying operational energy use and expenses associated with each treatment for the duration of the study were gathered from VNAP and Agrilab Technologies Inc. Each compost turning event was recorded, and fuel use and labor expenses were calculated for each treatment during the study. Agrilab Technologies Inc. assisted with electrical calculations associated with the operation of the CAHR system. Assumptions used to determine operational expense and energy use are provided in the Supplementary Material, Text S1.

To quantify the performance of the CAHR system holistically, not just for operational expense, we gathered data on capital expense, fuel/energy savings, and infrastructure cost savings for the CAHR system relative to conventional management. These data were sourced from a 2018 analysis of system performance at VNAP (Foster et al. 2018).

2.7 Data Analysis

Nutrient composition and economic data gathered during this study were compiled in Excel and plots were produced in R. Temperature and nutrient data shown in plots are averages of the 3 sample points taken weekly. Unless otherwise indicated, nutrient and TOC concentrations are expressed as percent by dry mass of compost. All statistical tests were conducted using the 2-sided, unpaired "t.test" function in base R to compare treatments on a weekly, monthly, or 13-week study period basis, unless $p < 0.05$ for the Shapiro-Wilk normality test (for monthly or 13-week study period). In such cases (13-week temperature, 13-week TOC, 13-week pH, and month 3 percentage of TP as WEP), the Mann-Whitney U test was used as a nonparametric alternative.

3. Results

3.1 Compost Temperature and Moisture Content

CAHR-treated compost sustained higher internal temperatures than were observed in conventional treatment (Fig. 1a). Note that because compost batches were mixed a few days before sampling began, compost temperatures had already risen well above ambient temperatures. Significantly higher temperatures were found for the CAHR treatment for 12 of the first 13 weeks (n=3 for each treatment each week, week 2 p=0.003, week 3 p=0.006, week 4 p=0.002, week 5 p <0.001, week 6 p <0.001, week 7 p=0.005, week 8 p=0.02, week 9 p <0.001, week 10 p=0.002, week 11 p=0.005, week 12 p=0.002, week 13 p <0.001) and for the 13-week period as a whole (n=39 for each treatment, p <0.001).

There was rapid decrease in moisture content following initially high aggregate temperatures in the thermophilic phase: maximum of 63 °C for conventional treatment and 77 °C for CAHR (Fig. 1b). The treatments displayed similar trends in moisture content over time, with increases in moisture content generally coincident with watering and rainfall events. Higher temperatures combined with constant aeration led to consistently drier material for the CAHR. Significantly lower moisture contents were observed in the CAHR treatment compared to the conventional treatment for 6 of the first 13 weeks (n=3 for each treatment each week, week 3 p=0.019, week 6 p=0.045, week 7 p=0.005, week 8 p=0.009, week 10 p=0.034, week 13 p=0.002) and for the 13-week period as a whole (n=39 for each treatment, p <0.001).

On September 15, 2021, VNAP staff watered the CAHR-treated windrow with ~33.3 m^3 of runoff from the onsite stormwater pond using a liquid manure tanker. The conventionally treated windrow received ~16.7 m^3. To mitigate the drying effects of consistent aeration and higher temperatures, the CAHR windrow received twice

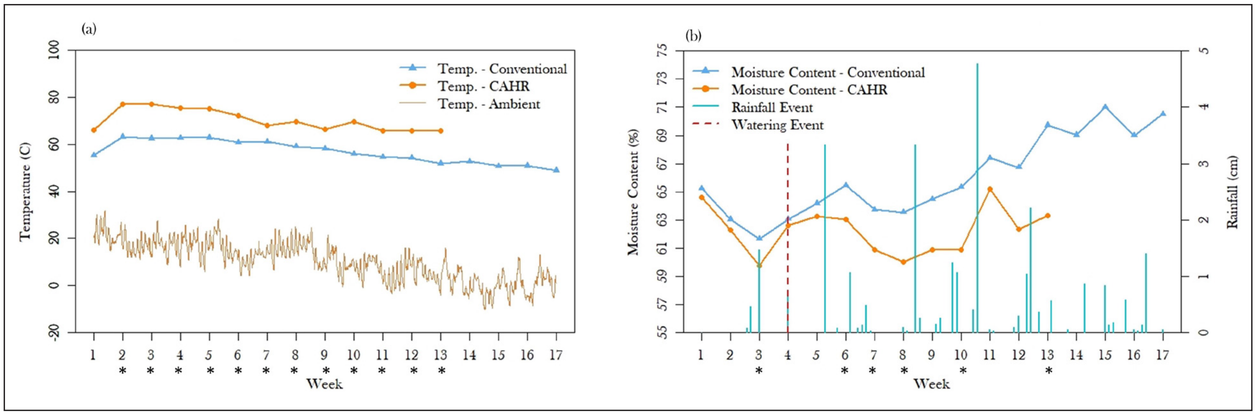

Fig 1. Temperature (Fig. 1a) and moisture content and rainfall (Fig. 1b) over time in the conventional and CAHR compost windrows. Each temperature data point in Fig. 1a is an average of the 48 temperature readings taken during each week. Each moisture content data point through week 13 in Fig. 1b is an average of the 3 composite samples taken during each week. For week 14 to week 17, each conventional data point is a single observation of the one composite sample taken that week. * denotes significant difference in temperature (Fig. 1a) or moisture content (Fig. 1b) between the CAHR and conventional test groups at α=0.05 (n=3 for each treatment, each week).

as much liquid as the conventional windrow. Composts were immediately turned to integrate the liquid, and a sample of the stormwater used was collected and sent for analysis at A&L. Masses of N, P, and K added through watering the conventional windrow were 1.33 kg, 0.17 kg, and 4.66 kg, respectively. Masses of N, P, and K added through watering the CAHR windrow were 2.66 kg, 0.34 kg, and 9.32 kg, respectively. Each addition of nutrients through watering was <1% of the total final mass of that nutrient estimated for each treatment and therefore deemed negligible for this study.

3.2 Carbon Dynamics

Initial TOC concentrations for the conventional and CAHR treatments were 45.3% and 46.8%, respectively (Fig. 2a). After 13 weeks, TOC concentrations were 44.7% for the conventional treatment and 44.4% for the CAHR treatment. By week 17, TOC had fallen to 40.5% for the conventional treatment. No by-week or 13-week study period significant differences between the treatments were found for TOC through week 13 (p >0.05).

Carbon to nitrogen ratio (C:N) began at 31:1 for the conventional windrow and 33:1 for the CAHR windrow, typical of fresh compost mixes at VNAP (Fig. 2b). The C:N ratio dropped more rapidly in the CAHR treatment throughout the early weeks of the study. Significantly lower C:N ratios were found in the CAHR treatment for 7 of the first 13 weeks (n=3 for each treatment each week, week 3 p=0.044, week 4 p=0.045, week 5 p=0.046,

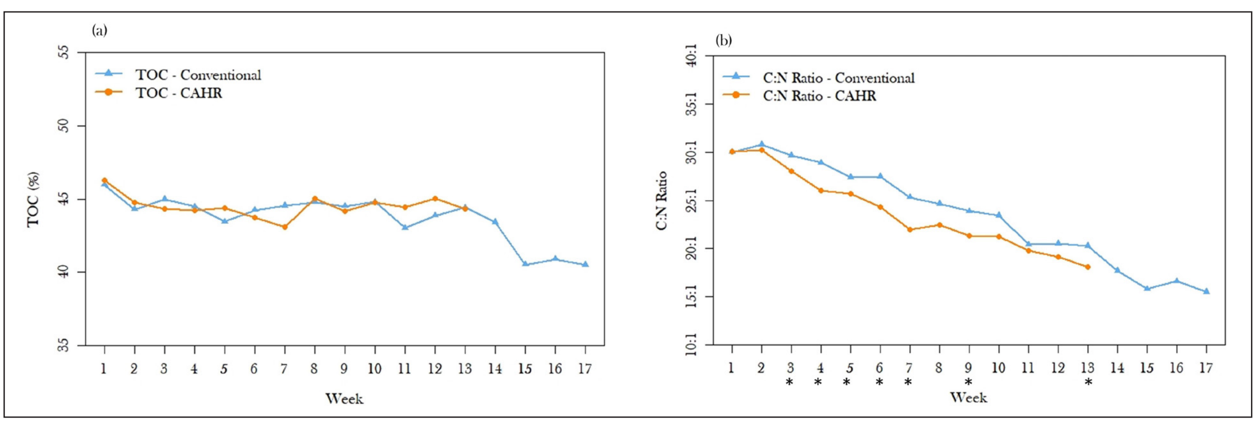

Fig. 2. Total organic carbon (TOC) (Fig. 2a) and carbon to nitrogen (C:N) ratios (Fig. 2b) in the conventional and CAHR compost windrows. Each data point through week 13 in Fig. 2 is an average of the 3 composite samples taken during each week. For week 14 to week 17, each conventional data point is a single observation of the one composite sample taken that week. * denotes significant difference in each test parameter between the CAHR and conventional test groups at α=0.05 (n=3 for each treatment, each week).

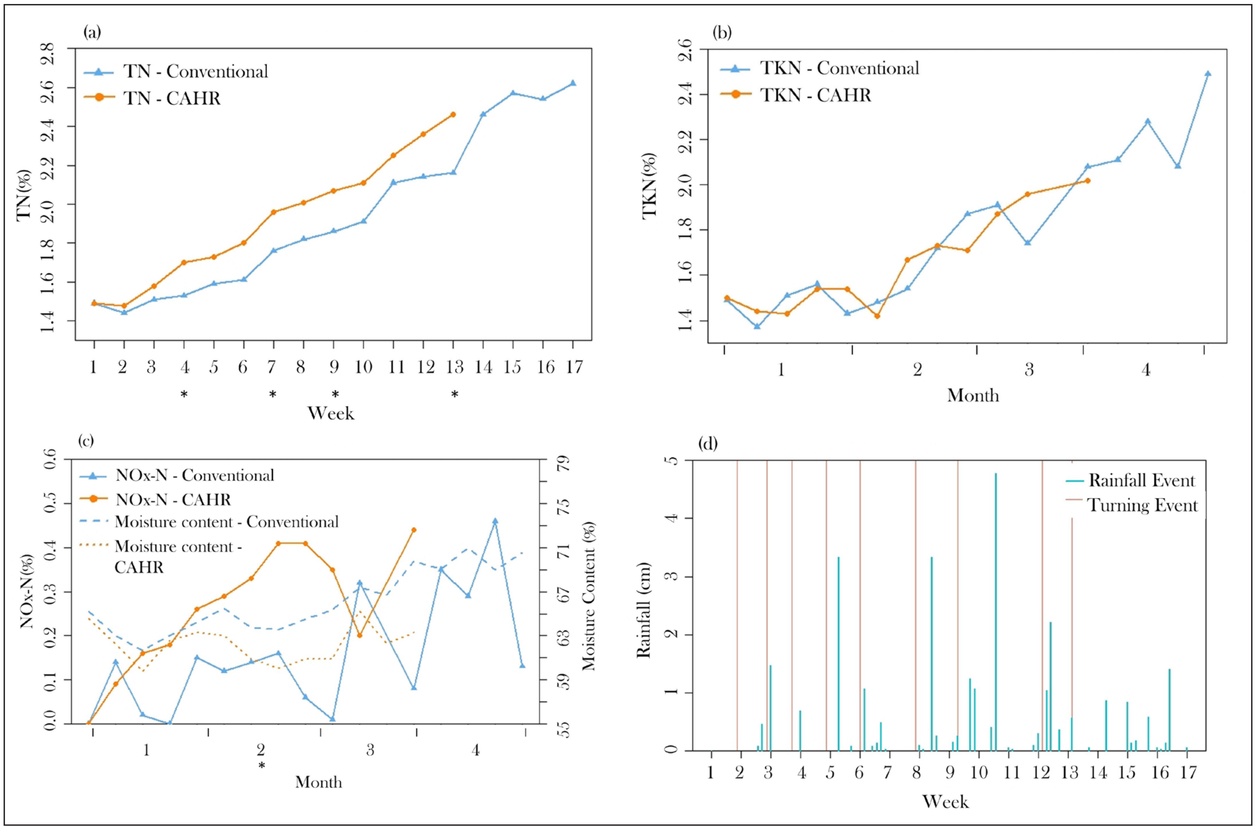

Fig. 3. Total Nitrogen (TN) (Fig. 3a), Total Kjeldahl Nitrogen (TKN) (Fig. 3b), and Nitrate + Nitrite Nitrogen (NO_x-N) (Fig. 3c) in the conventional and CAHR compost windrows, and (Fig. 3d) compost turning and rainfall events during the study period. Each data point through week 13 in Fig. 3 is an average of the 3 composite samples taken during each week. For week 14 to week 17, each conventional data point is a single observation of the one composite sample taken that week. For Fig. 3a, * denotes significant difference between TN in the CAHR and conventional test groups at α=0.05 (n=3 for each treatment, each week). For Fig. 3b and Fig. 3c, * denotes significant difference in TKN (Fig. 3b) or NO_x-N (Fig. 3c) between the CAHR and conventional test groups at α=0.05 (n=5, 4, and 3 for each treatment for months 1, 2, and 3 respectively).

week 6 p=0.017, week 7 p=0.004, week 9 p=0.022, week 13 p=0.020) and for the 13-week period as a whole (n=39 for each treatment, p=0.037).

3.3 Nitrogen Dynamics

Total nitrogen (TN) concentrations in both composts increased over time (Fig. 3a). Coinciding with the high temperatures around week 2, we observed TN percentages increase more quickly in the CAHR compost than the conventional treatment, suggesting that frequent aeration facilitated N preservation. Significantly higher TN concentrations were found in the CAHR treatment for 4 of the first 13 weeks (n=3 for each treatment each week, week 4 p=0.004, week 7 p=0.020, week 9 p=0.049, week 13 p=0.018) and for the 13-week period as a whole (n=39 for each treatment, p=0.018). After 17 weeks, conventional treatment resulted in an end product with slightly higher TN on a dry weight basis compared to the 13-week CAHR compost, consistent with the relationship between TN and duration found by Yang et al. (2019).

TKN data indicated similar weekly values for both treatments across the study period (Fig. 3b). No significant differences in monthly or 13-week aggregate values were found between the 2 treatments through week 13 (month 3) (p >0.05).

NO_x-N was significantly greater in the CAHR treatment for month 2 (n=4 for each treatment, p<0.001) and for the first 13 weeks as a whole (n=15, p=0.003) (Fig. 3c). In the CAHR windrow, 68% of the observed NO_x-N produced was retained, but only 13% was retained in the conventional windrow. Because both windrows produced similar magnitudes of observed NO_x-N through week 13, we hypothesize that the lower moisture content for the CAHR treatment provided conditions less conducive to NO_x-N loss.

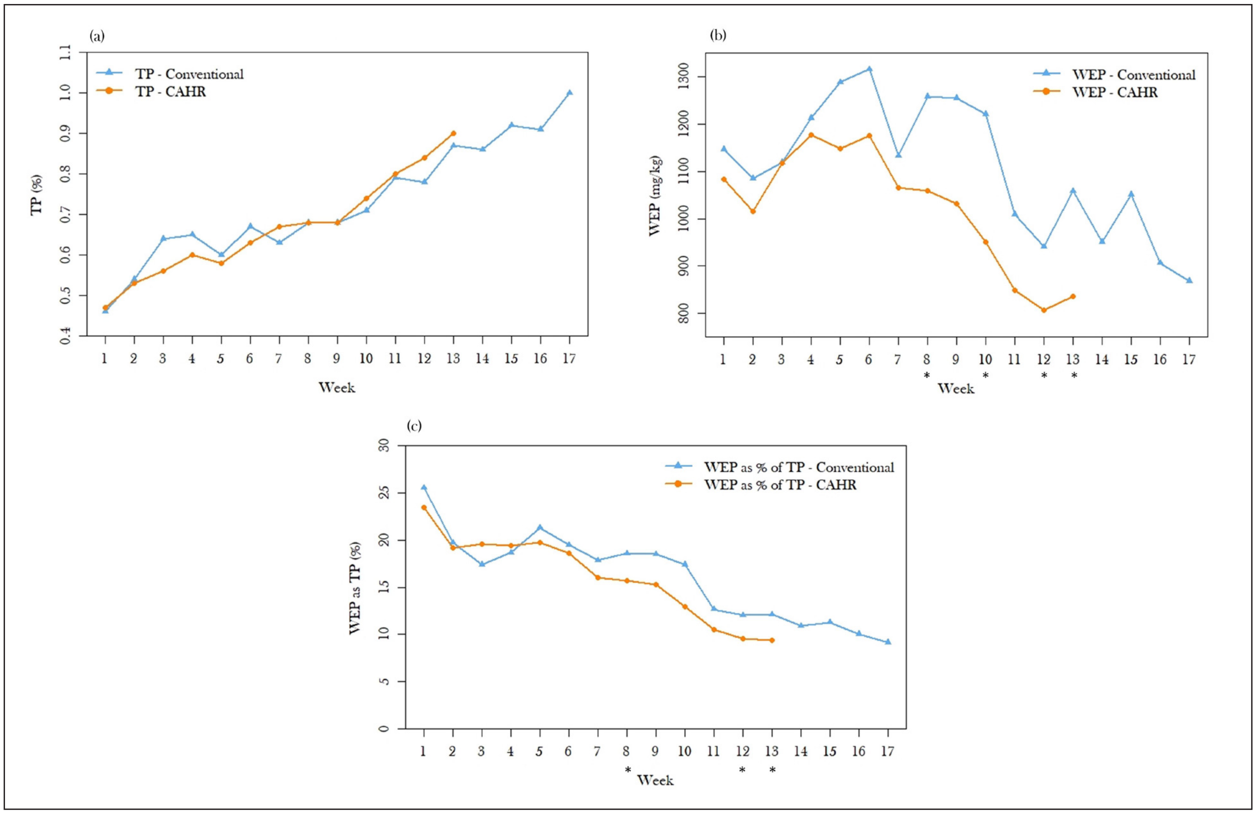

Fig. 4. Total Phosphorus (TP) (Fig. 4a), Water-Extractable Phosphorus (WEP) (Fig. 4b), and Water-Extractable Phosphorus (WEP) as % of Total Phosphorus (TP) (Fig. 4c) in the conventional and CAHR compost windrows. Each data point through week 13 in Fig. 4 is an average of the 3 composite samples taken during each week. For week 14 to week 17, each conventional data point is a single observation of the one composite sample taken that week. For Fig. 4b and Fig. 4c, * denotes significant difference in each test parameter between the CAHR and conventional test groups at $\alpha=0.05$ (n=3 for each treatment, each week).

3.4 Phosphorus Dynamics

We saw only slight differences between conventional and CAHR-treated composts for TP concentrations, with the conventionally treated windrow trending higher than the CAHR treatment after week 13 (Fig. 4a). No weekly or aggregate significant differences were found for TP between the treatments through week 13 ($p > 0.05$).

Average WEP concentrations through week 13 were 1157 mg P/kg and 1024 mg P/kg for the conventional and CAHR treatments, respectively (Fig. 4b). Significantly lower WEP concentrations were found in the CAHR treatment for 4 of the first 13 weeks (n=3 for each treatment each week, week 8 p=0.038, week 10 p=0.025, week 12 p=0.038, week 13 p=0.008), as well as for months 2 and 3 of the study (n=13 and n=12 for month 2 [p=0.007] and month 3 [p <0.001]), and for the 13-week period as a whole (n=39 for each treatment, p <0.001).

CAHR-treated compost had a consistently lower WEP as a percentage of TP than did the conventional treatment from week 5 onward (Fig. 4c). Significantly lower WEP as a percentage of TP was found in the CAHR treatment for 3 of the first 13 weeks (n=3 for each treatment each week, week 8 p=0.006, week 12 p <0.001, week 13 p <0.001) and for months 2 and 3 of the study (n=13 and n=12 for months 2 [p=0.021] and 3 [p=0.004]).

3.5 pH

pH values rose in the conventional windrow through the first 4 weeks of the study and roughly followed the slightly decreasing trend of the CAHR treatment thereafter. pH for the conventional and CAHR treatments began at 8.1 and 8.3 and ended at 7.8 and 7.5, respectively. pH was consistently higher in the conventional compost after week 2, and the treatments were significantly different for 5 of the first 13 weeks (n=3 for each treatment each week, week 2 p=0.038, week 4 p=0.033, week 6 p <0.001, week 8 p=0.030, week 12 p=0.008), as well as for the 13-week period as a whole (n=39 for each treatment, p <0.001).

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

		Conventional		CAHR	
Test Parameter	**Units**	**Initial value 8/24/2021**	**Final value 4 months**	**Initial value 8/24/2021**	**Final value 3 months**
TN	%	1.4	2.6	1.4	2.6
TKN	%	1.5	2.5	1.3	2.0
(NO_2-N + NO_3-N)	%	below detection	0.1	0.1	0.6
N as NO_x-N	% of TN	N/A	5.0	8.3	22.0
P	%	0.4	1.0	0.5	0.9
WEP	mg P/kg	885	869	1083	841
P as WEP	% of TP	21	9	20	10
K	%	1.2	2.5	1.3	2.3
N-P-K	%	1.4-0.4-1.2	2.6-1.0-2.5	1.4-0.5-1.3	2.6-0.9-2.3
TOC	%	45	41	47	44
C:N Ratio	-	31	16	33	17
N:P Ratio	-	3.4	2.6	2.7	2.9
pH	-	8.1	7.8	8.3	7.5
Fecal Coliforms	MPN/g dry	2	10	2	4430
Germination	%	100	100	100	100
Respiration	mg CO_2/g OM/day	1.4	1.4	1.4	1.2

3.6 Major Compost Testing Metrics and Mass Balance Analysis: Overall Results

Table 1 shows the major compost testing metrics on a dry weight basis. Values included in this table are from the initial and final sampling dates for each treatment and provide a succinct comparison of the resulting composts produced by each treatment method.

Mass balance results for major compost nutrients are shown in Table 2.

Table 2 Mass balance for major compost nutrients. Bulk densities are given on a wet weight basis.

	Test Parameter	Bulk Density	Volume	N	P	K	TOC
	Units	**kg/m³**	**m³**	**kg**	**kg**	**kg**	**kg**
Conventional	Initial value 8/24/2021	540	367	991	297	833	31665
	Final value 4 months	656	179	903	340	845	14009
	Retention (%)	N/A	49	91	114	101	44
CAHR	Initial value 8/24/2021	516	420	1125	411	973	36206
	Final value 3 months	574	245	1291	435	1165	22514
	Retention (%)	N/A	58	115	106	120	62

Notes: Initial and final moisture contents for the conventional windrow were 64.7% and 70.5%, respectively. Initial and final moisture contents for the CAHR windrow were 64.2% and 63.9%, respectively. These moisture contents are on a wet weight basis.

Table 3 Operational financial cost and energy use in the conventional and CAHR composting systems

	Conventional			CAHR		
m^3 finished compost	197			245		
Operational Activity	**Financial Cost ($)**		**Energy Use (kWh)**	**Financial Cost ($)**		**Energy Use (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 m^3 finished compost)	$	0.44/m^3	0.68 kWh/m^3	$	0.93/m^3	3.74 kWh/m^3

Note: See Supplementary Material, Table S1 for detailed operational expense and energy use calculations.

3.7 Financial and Energy Analysis

Results of the operational financial and energy analysis are provided in Table 3.

The calculations in Table 3 only account for normal operational inputs from the time compost batches were assembled until they were removed from production. This study did not monitor time and space savings provided by a managed aeration system and did not monitor 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 4 (Foster et al. 2018). Additional details on cost analysis are given in the Supplementary Material, Text S6.

Table 4 presents expense and cost savings values of the CAHR system throughout its lifetime of construction, operation, and use relative to conventional compost management.

Table 4 Cost savings per cubic meter of finished compost for the CAHR composting system relative to the conventional system. A $ amount shown in parentheses indicates an expense for the CAHR, while a $ amount shown without parentheses indicates savings when using the CAHR.

Cost Savings Parameter	CAHR	
Operational cost	$	(0.49)
Capital expense (adapted from Foster et al. 2018)	$	(3.79)
Energy/Heating cost savings (Foster et al. 2018)	$	2.68
Avoided infrastructure cost savings (Foster et al. 2018)	$	3.11
Total savings (per m^3 finished compost)	$	1.51

Considered in the energy and heating cost savings are the reduced demand for #2 heating oil used to heat the VNAP packaging building and propane used to dry composts prior to bagging. Biologically generated heat captured from composts by the CAHR system is an example of ecological engineering in practice and reduces demand for fossil fuel sources. The avoided infrastructure cost savings approximate expansion expenses that VNAP avoids through adoption of the CAHR system. If the CAHR system was not implemented, the facility would need to be expanded, as a greater pad area and stormwater pond volume are required to process conventionally turned windrows while still meeting annual product demand. It should be noted that these cost savings estimates are based on 2018 prices for installation of the CAHR system, #2 heating oil, propane, permitting, and earthwork, among others. These factors considered, we estimate that the CAHR system, as operated at VNAP, could save a compost producer $1.51/$m^3$ of finished compost when compared to conventional windrow composting.

4. Discussion

4.1 Compost Temperature

Microbial communities in the CAHR system were supplied more O_2, theoretically increasing microbial activity and compost temperature (Yang et al. 2019). It should also be noted that the relatively high specific heat of water means that drier compost mixtures can heat and cool more rapidly than wetter mixtures (Trautmann et al. 1996). More careful monitoring of the CAHR compost was needed by VNAP staff to regulate windrow temperature. Sustained temperatures above 70 °C are harmful to many bacterial communities and fungi (Mengqi et al. 2023; Rastogi et al. 2020) and should be avoided to preserve the microbial diversity of the compost and avoid hampering degradation rates (Onwosi et al. 2017). However, it is generally accepted that temperatures should be kept greater than 55 °C – 60 °C for at least 1 week to ensure pathogen and seed elimination (Bernal et al. 2009; Mengqi et al. 2023). Both composts achieved temperatures sufficient for pathogen kill, but the CAHR compost experienced slightly higher than ideal temperatures through week 6 despite careful monitoring.

Although CAHR-treated compost required more monitoring, the time benefits of higher temperatures and constant aeration were noticeable. From a practitioner's standpoint, the CAHR-treated compost was deemed suitable for market by VNAP 4 weeks before its conventionally treated counterpart.

4.2 Nutrient Dynamics

As organic materials degrade during composting, the mass and volume of the material both decrease due to the breakdown of structural organic components and mineralization of organic matter to CO_2 and H_2O, concentrating other constituents (Breitenbeck and Schellinger 2004). Therefore, the increases in nutrient concentrations that we observed over time (Fig. 3a and Fig. 4a) are to be expected. Because of the lack of difference in TOC concentrations between the treatments, the early departure in C:N ratios can be linked to higher N preservation in the CAHR treatment. It is suggested in a review 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. Overall, lower TOC mass retention and C:N ratio were observed for the final conventional compost than the CAHR compost, which are attributed to the continued oxidation of organic matter by microbes between week 13 and week 17.

Evaluating N speciation throughout the study period reveals some interesting trends. Nitrate N is a highly available N source for plants (Hoang et al. 2022) and is ideally preserved in composts. NO_2-N and NO_3-N are produced by nitrifying bacteria in the presence of O_2, but can be lost through leaching (i.e., during heavy rain events) or through denitrification in the absence of O_2, when NO_3-N can be converted to gaseous forms of N, including dinitrogen gas (N_2) and N_2O, the latter being a potent GHG (Hoang et al. 2022; Yang et al. 2019). While N_2 is the dominant end product of denitrification, some N_2O emissions can occur during incomplete denitrification (USEPA 2020). N_2O production can also occur during nitrification, although production rates have been found to be lower than during denitrification (Khalil et al. 2004; Zhang et al. 2015).

Because the conventionally treated windrow received less O_2 and was more likely to form anaerobic zones (especially when wet), we hypothesize that more denitrification, which requires anaerobic conditions, occurred in the conventional windrow, and that gaseous N losses resulted.

When NO_x-N decreased, it is also possible that some NO_3-N was lost to the environment through leaching. However, because of the high retention of P and K shown in Table 2, as well as low levels of N in the onsite stormwater pond, we do not believe that NO_x-N leaching was a primary driver of N loss for either compost. This is consistent with low N leaching losses relative to gaseous N losses found by others (Chowdhury et al. 2014; Wang et al. 2021; Yang et al. 2019).

Another possibility for gaseous N loss from the conventional windrow is ammonia (NH_3) volatilization. If the conventional windrow was losing NH_3 and the CAHR windrow was more effectively converting ammonium to nitrate, these 2 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. In the CAHR windrow, more rapid NH_3 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 through the first 4 weeks of the study may have been an indicator for increased N loss through NH_3 volatilization (Bernal et al. 2017).

Overall, the data suggest that the CAHR treatment and associated aeration was more effective in preserving NO_x-N during composting, curtailing undesirable N losses to the environment. Further research, including gaseous analysis, is needed to expand understanding of N loss dynamics and would complement the findings of Chowdhury et al. (2014), Ma et al. (2020), Sun et al. (2018), and Yang et al. (2019).

As we did not perform gaseous analysis as a component of this study, we cannot determine with certainty which treatment was more prone to GHG loss through methane (CH_4) or N_2O release, both potent GHGs (Ermolaev et al. 2015; Hao et al. 2002; Zhang et al. 2015). It is possible that higher N_2O and CH_4 generation potential existed in the conventionally treated windrow characterized by lower temperatures and higher moisture (Fig. 1), as anaerobic zones were more likely to form (Ma et al. 2020). It has been shown that lower temperatures and higher moisture content in composts correlate to higher N_2O and CH_4 releases (Ermolaev et al. 2015, 2019).

The WEP data suggest that the CAHR treatment provided better protection against P loss, possibly through immobilization by microbial communities and more stable iron (Fe)-P due to more prominent aerobic conditions (Kjaergaard et al. 2012). In addition, lower moisture content in the CAHR windrow throughout the composting period may have reduced its potential for

P loss, as CAHR compost could accommodate more rainwater before leaching occurred.

Although this is positive for P retention during the composting process, the presence of aerobic conditions is not guaranteed for the end use of the compost, and P loss could occur if the compost were to encounter saturated or anoxic conditions in a field setting (Kjaergaard et al. 2012; Kleinman et al. 2005). Furthermore, due to the varied abilities of aluminum, Fe, and calcium to sorb P at different pH levels, the P retention ability of either compost could change when incorporated in soil (Penn and Camberato 2019).

4.3 Major Compost Testing Metrics

N-P-K contents in the conventionally treated final compost were 100%, 111%, and 109% of the N-P-K values in the CAHR final compost, respectively (Table 1). For both treatments, final N-P-K values, as well as the major metrics of TOC and C:N ratio, were within typical ranges (e.g., 0.5% – 3.3% N, 0.1% – 1.5% P, 0.1% – 3.9% K, ~9% – 54% TOC, C:N = 8.6 – 25.5) previously observed for mature manure-based composts (Bernal et al. 2017; Schwarz and Bonhotal 2017; Zhen et al. 2021).

Germination rate and CO_2 respiration rate for both treatments changed little between the first and last days of sampling, but both were suggestive of mature or stable compost. It has been suggested that a germination rate of >50% (Bernal et al. 2009) and a CO_2 production rate <9.6 mg CO_2/g OM/d (Bernal et al. 2017) can both be used to proxy compost maturity. By these metrics, both treatments could have been considered mature or stable during the entirety of the study, and data were not substantive enough to make declarations of compost maturity. However, the experience of VNAP staff in determining mature compost should not be discounted, and careful evaluation of compost color, aroma, and particle size (Bernal et al. 2009, 2017; Onwosi et al. 2017) was undertaken to determine, at the very least, the stage of decomposition of the feedstock materials, which is supported by final C:N ratios <20:1. A discussion of fecal coliform data presented in Table 1 is given in the Supplementary Material, Text S7.

Given that both windrows had N-P-K concentrations and C:N ratios typical of finished composts, it is reasonable to conclude that the CAHR system produced a comparable product in 13 weeks, 4 weeks shorter than the conventional treatment's 17 weeks to maturity. Note that maturity is not merely a function of time, but of the characteristics of input feedstocks and the combined evaluation of humification, microbial stability, C:N ratio, odor, color, nutrient content, and pathogen removal (Bernal et al. 2009, 2017). The compost maturation time scales observed in this study are consistent with industry expectations for dairy-manure-dominant feedstocks within the region (e.g., ~12 weeks for CAHR systems, <8 months for windrows with an aggressive turning regime) (Kryzanowski 2019; Vermont Agency of Natural Resources 2015).

4.4 Mass Balance

In the mass balance (Table 2), we computed values above 100% for many nutrient retention parameters, which suggests nutrient input. This is unlikely, as annual atmospheric deposition rates of N, P, and K are many orders of magnitude smaller than the total masses of N, P, and K in the windrows (Mahowald et al. 2008; Mikhailova et al. 2019; Zhang et al. 2012). Using bulk density measurements to estimate total windrow wet mass based on estimated volume likely affected our mass balance results because in situ bulk density is very difficult to measure accurately (Agnew and Leonard 2003) and it is also difficult to measure the volume of commercial-scale windrows exactly. Furthermore, it is challenging to sample windrows in a perfectly representative fashion, so our estimates may be affected by within-windrow variability in both bulk density and nutrients. Despite these potential sources of error, our consistent use of measurement methods allows us to assess some general trends between treatments.

Of N, P, and K, the only mass loss estimated (i.e., mass retention <100%) was for N in the conventional treatment. The mass balance supports our analyses suggesting that the conventional windrow suffered more N losses than the CAHR windrow, with denitrification, nitrate leaching, and/or NH_3 volatilization playing roles (Hoang et al. 2022; Yang et al. 2019; Zeng et al. 2012). The conventional windrow was also more susceptible to environmental nutrient loss due to the additional 4 weeks of composting time. Additionally, the relative losses of C, N, P, and K in this study are comparable to loss rankings found by others (loss of C > loss of N > loss of P and K) (Larney et al. 2006; Luebbe et al. 2011; Tiquia et al. 2002), especially for the conventional treatment.

4.5 Financial and Energy Analysis

The operational expense and energy use data (Table 3) suggest that conventional management of composts is less expensive than using the CAHR system with turned aerated piles (TAPs). It is important to note that a CAHR system installed at a facility managing its compost as aerated static piles (ASPs) could achieve higher thermal efficiency and lower operating costs due to the consolidation of product within larger piles or bins and the reduced demand for turning and watering (Agrilab Technologies Inc. 2022). Note also that the typical management strategy at VNAP, and of TAP CAHR systems at large, provides less frequent turns for the CAHR windrows than was observed during this study, reducing the CAHR's operational costs. Typically, the CAHR windrow is turned approximately one of every 2 turns of the conventional windrow (Foster et al. 2018), as opposed to the 8:9 turn ratio observed in this study. Therefore, operational costs concurrent with this study and the management of composts during this study may be conservative estimates and should not be considered representative of all CAHR systems.

Additionally, as shown in Table 2, a larger volume fraction remained in the CAHR windrow, which is attributed to its shorter composting duration. This provides additional benefit to the producer, as there is more compost available for sale. While sales value of compost was not directly accounted for in the economic analysis, it has been shown that the CAHR is the more space-efficient method of curing compost at VNAP (Foster et al. 2018) and is likely to increase gross sales volume. As is shown in Table 4, a CAHR system can provide cost savings to a producer when reduced heating fuel demand and reduced need for compost yard enlargement are factored against operational costs and capital expense.

5. Conclusion

This case study evaluated nutrient status, financial cost, and energy use 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 25% less time than a conventionally turned windrow. Analysis of N species status throughout the study suggests that greater N losses to the environment occurred during conventional treatment than during CAHR treatment, hypothesized to be driven by greater rates of denitrification and NH_3 volatilization. Data also suggest a lower risk for P loss through leaching from CAHR-treated compost, as WEP concentrations were consistently greater in the conventional treatment. During the active composting process, it was found that operational costs for CAHR compost were 2.1 times greater and energy use was 5.5 times greater than for a conventional compost on a per m^3 basis. However, the fuel and infrastructure cost offsets (i.e., reductions in heating oil and propane demand and reduced need for facility expansion due to time-space efficiencies) provided by the CAHR system (as operated at VNAP) could provide a net savings of $1.51/$m^3$ finished compost. In this case study, it was shown that a CAHR system produced a comparable compost product, with higher operational input, in less time, while reducing overall fossil fuel demand, decreasing GHG emission risk, and reducing nutrient loss.

Supplementary Material

The online version of this article contains a link to supplementary material that includes: Table S1 Operational expense and energy use calculations; Text S1 Assumptions used to determine operational expense and energy use; Text S2 Management of composts by VNAP staff; Text S3 Atmospheric Data Collection; Text S4 NO_x-N produced and lost for each treatment; Text S5 Potassium results; Text S6 Detailed cost analysis figures; Text S7 Fecal coliforms discussion.

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Conceptualization: JWF, EDR; methodology: FAB, JWF, EDR; data analysis: FAB; laboratory analyses: FAB; writing original draft: FAB; review/editing original draft: JWF, EDR; investigation: FAB; resources: JWF, EDR; data curation: FAB; supervision: JWF, EDR; project administration: JWF, EDR; funding acquisition: JWF, EDR. All authors have read and agreed to the published version of the manuscript.

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The authors have no conflict of interest to report.

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