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Energy recovery from commercial-scale composting as a novel waste management strategy

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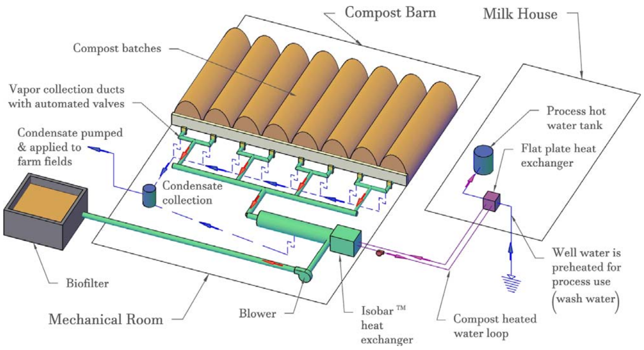
HIGHLIGHTS

- Energy recovery rates from a commercial-scale composting facility are presented.
- Compost vapor between 51 and 66 °C resulted in recovery rates of 17,700–32,940 kJ/h.
- Energy recovery was directly related to compost vapor and heat sink temperatures.
- Temperature lag times between initiation of aeration and system equilibrium existed.
- Temperature lag times warrant unique aeration schedules to maximize energy recovery.

GRAPHICAL ABSTRACT



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ABSTRACT

This study reports operational information from a commercial-scale Aerated Static Pile (ASP) composting system with energy recovery, one of the few currently in operation globally. A description of this innovative system is followed by operational data on energy capture efficiency for 17 experimental trials with variable compost vapor and heat sink temperatures. Energy capture was directly and predictably related to the differential between compost vapor and heat sink temperatures, with energy capture ranging from 17,700 to 32,940 kJ/h with a compost vapor temperature range of 51–66 °C. A 5-day temperature lag time existed between compost pile formation, and when compost vapor temperatures were sufficiently high for energy recovery (≥50 °C). The energy recovery system also exhibited a time lag between the initiation of aeration and when the vapor reaching the heat exchanger reached pile vapor temperature. Consequently, future ASP composting sites employing an energy recovery system may have to alter aeration system design and schedules to compensate for any type of heating-up phase that reduces energy recovery.

1. Introduction

Industrial-scale composting is growing rapidly in the United States, due to increased restrictions on the disposal of organic waste in landfills [1]. This, combined with concerns regarding global climate change, have reinvigorated the discussion of innovative methods of composing, and whether the heat released from the composting process is a viable alternative energy source for localized heating needs. With compost

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Abbreviations: ASP, Aerated Static Pile; HST, heat sink tank; CHRS, compost heat recovery system; PVC, polyvinyl chloride; NHAES, New Hampshire Agricultural Experiment Station; USDA, United States Department of Agriculture; SARE, Sustainable Agriculture Research and Education

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pile and vapor temperatures often exceeding 70 °C for several weeks at a time [2], there is a potentially valuable and recoverable resource being released to the environment at many composting sites.

The recovery of energy from the composting process has a long history, dating back to hotbed systems used in China 2000 years ago [3]. However, research on how to capture the microbially-produced heat for beneficial use has been primarily focused on lab-scale [4–7] or pilot-scale [8–11] systems that were never applied in a commercial setting. Of the few peer-review studies describing compost heat recovery systems (CHRS) suitable for a commercial operation [12–16], all involved modeling of a theoretical CHRS. Of the literature describing actual commercial-scale CHRSs, all were published in practitioner-based sources [17–21], where the focus was on describing the CHRS and composting operation in general. Excluding Allain [17], few details have been reported about how changing compost parameters or management effect rates of energy recovery.

While the current combination of peer-reviewed and practitioner-based literature sources offer valuable insight into the ability to recover energy from the composting process for beneficial use, there is a considerable knowledge gap on how changing compost parameters or management strategies effect rates of energy recovery from an actual commercial-scale composting operation. Smith et al. [2] noted this lack of accurate quantitative data in their detailed literature review of CHRSs, and how a majority of studies reported only maximum energy recovery rates using compost vapor and pile temperatures that are not often sustained in the long run. For practitioners trying to decide between various waste-to-energy strategies, the lack of data from actual commercial systems poses a problem.

The lack of available data on commercialization of compost energy recovery systems is also evident in current review articles describing various methods used to recover energy from waste feedstocks [22–28]). In these articles, composting systems with energy recovery were not mentioned as a waste-to-energy strategy. Instead, the focus was on combustion/incineration, gasification, pyrolysis, anaerobic digestion and bio landfills. This is despite commercial composting operations with energy recovery having over a decade of proven success [2]. However, apart from the composting facility in the present study, these commercial operations are not research-based and do not publish results or disclose information regarding their energy recovery technology. They are simply focused on producing compost for sale and using the recovered heat for on-site purposes.

In this study, we report energy recovery rates from an active commercial-scale research composting facility, the only one of its kind globally. The primary parameters studied were compost vapor temperature and the hot water utilization from the recovery unit. This study is unique in that it is the first to present a true range of energy recovery values from a commercial-scale composting operation, based on changing operational parameters, rather than yields from the short-term, highest heat phase of the composting process. This type of information will be of value to practitioners planning composting systems with energy recovery, as it presents a more comprehensive view of the energy recovery potential during a complete composting cycle. This research will also be useful to policy analysts seeking innovative waste management strategies capable of energy recovery and offsetting greenhouse gas emissions through fossil fuel avoidance. Finally, it is our hope that this study will prove that recovering energy from composting is a viable strategy to recover energy from waste.

2. Materials & methods

2.1. Experimental facility

This research was conducted at the Joshua Nelson Energy Recovery Composting Research Facility at the Burley-Demeritt Farm in Lee, New Hampshire. The farm is part of the University of New Hampshire and is managed and operated by the New Hampshire Agricultural Experiment Station (NHAES).

The ASP composting facility processes dairy and equine manure, spent animal bedding (pine wood shavings), and waste feed hay. Monthly batches containing 115 m^3 (68 Mg wet weight or 27 Mg dry weight) of feedstock are loaded into the facility with a rear-discharge manure spreader. Standard compost residence time is 60 days, resulting in an annual composting volume of 2800 m^3 or 1655 Mg wet weight. This is a longer than traditional residence time and is designed to allow testing of a wider range of operational parameters than can be sustained in a commercial operation. If using a more standard 3–4 week turnaround, the facility would have a 5960–7950 m^3 composting throughput.

The facility was designed in conjunction with Agrilab Technologies, using concepts developed from their first CHRS at a dairy operation in Vermont, USA [21]. Feedstocks are aerated by pulling ambient air down through the piles with a 1 HP blower (NY Blower 126 CGI), which is connected to a network of perforated PVC pipes located below each composting bay. Vapor from each bay is routed through a manifold of PVC pipe to a specialized heat exchange system designed by Agrilab Technologies. The blower is located after the CHRS, so that vapor passes through the piles, into the aeration channels, through the manifold and into the heat exchange unit, which contains a 1117-liter heat sink tank (HST). Water from the HST is sent to the farm's milk house through an underground insulated PEX pipe, where it is used for hot water heating needs. Exhaust vapor post-heat exchanger is sent through a woodchip biofilter and released to the atmosphere [29] (Fig. 1).

The blower is controlled by a programmable logic controller (Do-More H2 Series) which also drives an air compressor and a series of pneumatic gate valves (Valterra 6401P) located at the header of every composting bay. The valves open and close according to a programmed aeration schedule for each bay, determined by incoming compost vapor temperature and oxygen concentration.

2.2. Experiments and data acquisition

Energy recovery from this system was determined by changes in temperature in the HST over time. Prior to each energy recovery trial, the aeration system was turned off and the HST drained and refilled with 13 °C well water. Upon refilling the HST, the aeration system was turned back on. Vapor from a single set of bays was used for each trial, and aeration was continuous for the duration of each 3–4 h trial. Because heat exchange is also dependent on the relative humidity and the flow rate of the compost vapor stream, both were held constant at 100% relative humidity and 7 m^3/min, respectively.

Data were collected for a total of 17 trials in May and June 2016. The compost recipe for all trials was a mixture of 40% cow manure, 40% horse manure/bedding mix and 20% waste hay. Vapor temperatures varied due to pile age and minor compositional differences in the compost mixtures. For each trial, vapor was drawn continuously through a single compost batch to assure a constant vapor temperature input to the heat exchanger. Vapor temperatures were recorded on one-minute intervals at every bay header, before and after the heat exchange unit and before the biofilter, using a Web Energy Logger (WEL). Two additional WEL sensors recorded the temperature within the HST (top and bottom) and another recorded ambient air temperature in the mechanical room of the facility. Compost pile temperatures were also recorded using a 2-meter ReoTemp temperature probe at a depth of 1 meter during the first 3 days following pile formation and weekly thereafter. All temperature data were input and analyzed in JMP Pro 13 SAS statistical software.

Energy capture was estimated as the change in water temperature, combined with the specific heat of water and the amount of water in the HST. If 1 kilojoule (kJ) is equivalent to the amount of energy required to raise 1 kg of water 0.24 °C, and the HST contains 1117 kg of water, the following equation was used:

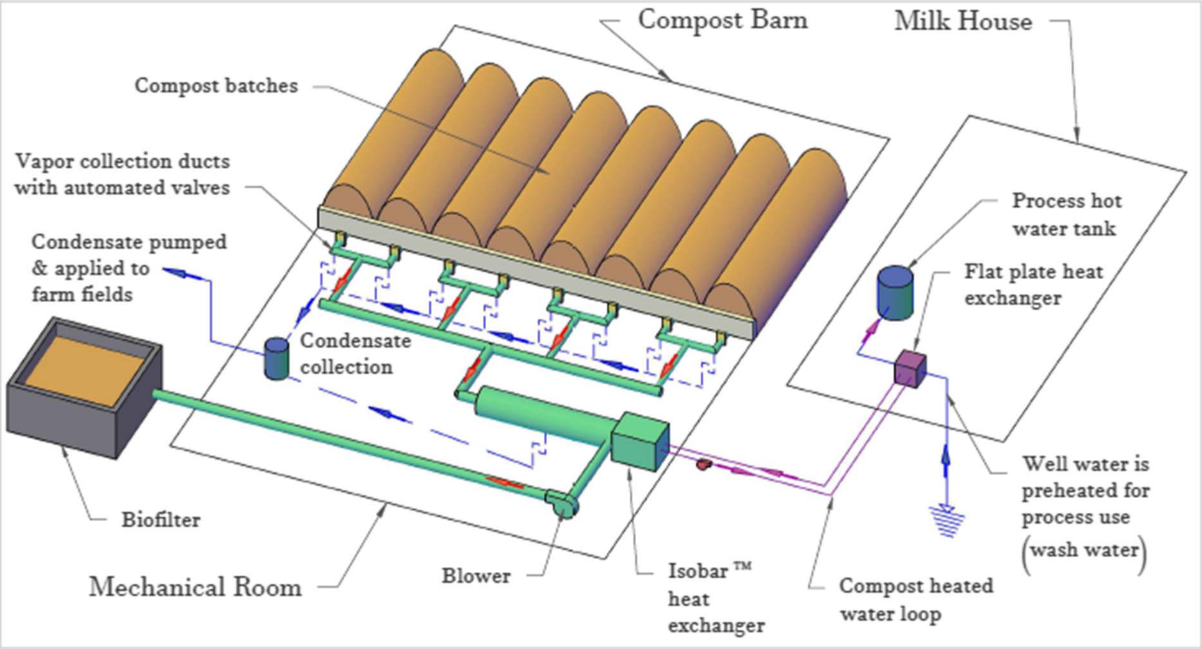

Fig. 1. Conceptual diagram of the University of New Hampshire energy recovery composting facility.

$$\text{Energy Recovery (kJ/min)} = \Delta T_{HST}/0.24\ ^{\circ}\text{C}*1117\ \text{kg} \quad (1)$$

where ΔT_{HST} is the change in water temperature in the HST for each one-minute interval for which data were collected.

3. Results and discussion

3.1. Timing of heat delivery

There was a time lag between the initiation of aeration for any bay and the time that the vapor temperature measured at the heat exchanger reflected the temperature at the headwall (Fig. 2).

This delay was due to energy losses (conductive and latent) occurring as the heated compost vapor passed through the cooler aeration ductwork prior to the CHRS. While the average temperature difference between the headwall and heat exchange unit for all 17 trials was 4.4 °C following the first minute of aeration and 1.3 °C by minute six, this warmup phase represents a loss in energy recovery that could potentially be avoided through alterations to the aeration schedule. In the present study, the aeration system was turned off while the HST was filled with well water, causing the aeration network to temporarily cool down. However, many commercial ASP composting systems have standard aeration off cycles, which allow pile temperatures to build or maintain at a set level. If maximum energy recovery is a goal, reducing these off cycles, possibly by reducing fan speed while increasing aeration on time, may be beneficial to reduce system cooling, which reduces energy recovery.

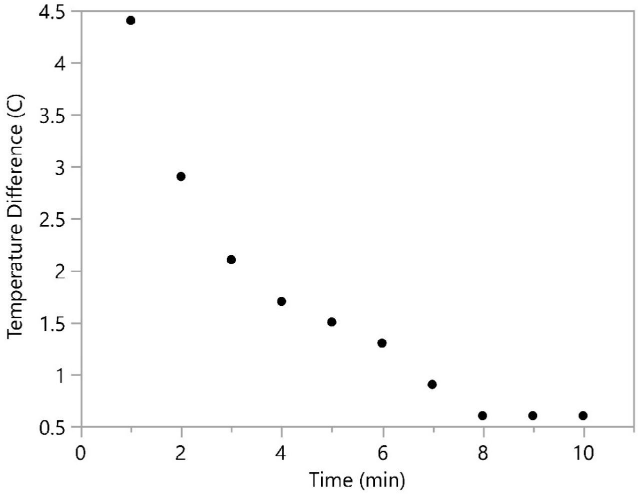

Fig. 2. Average compost vapor temperature difference between the headwall and heat exchange unit by time since initiation of aeration for 17 trial runs.

Following this startup period, the temperature of the compost vapor stream at the inlet to the CHRS remained constant over the 3–4 h trial period, while water temperature in the HST increased asymptotically (Fig. 3).

3.2. Rate of energy capture

On a per run basis, rates of energy capture changed continuously over time and were, as expected, directly related to the differential in

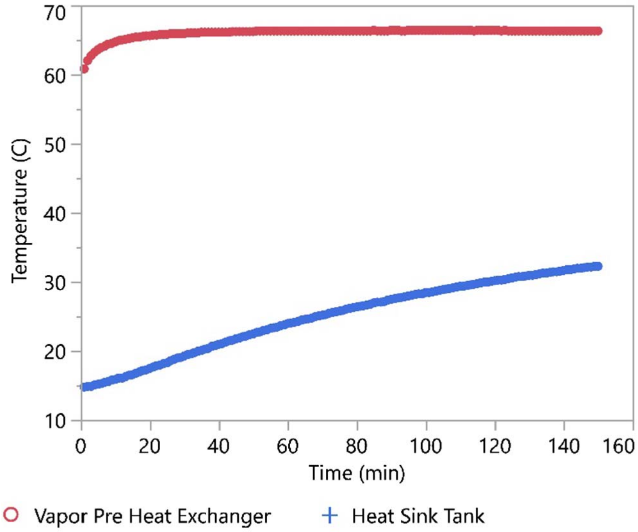

Fig. 3. Changes over time in the temperature of the vapor stream from the composting system pre-heat exchanger and the water in the heat sink tank (HST).

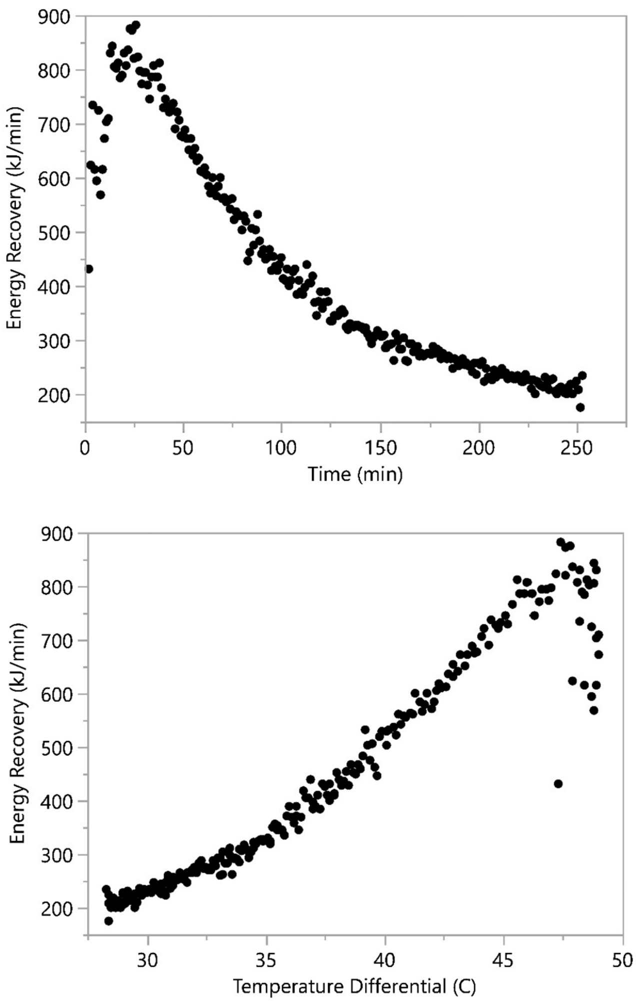

Fig. 4. Energy gain from the aerated static pile (ASP) composting system during a 4-h trial (see text for description). Top – changes in energy gain over time. Bottom – energy gain as a function of the difference in temperature between the vapor stream from the compost system and the water in the heat sink tank (HST).

temperature between the inlet compost vapor stream and the water in the HST (Fig. 4).

An initial discontinuity in this relationship occurs over the first 20 min, when temperatures at the inlet to the CHRS do not yet reflect temperatures at the headwall (Fig. 4). When removing data from this initial start-up period, the relationship between the temperature differential and rate of energy capture becomes highly significant (Fig. 5) ($P < .0001$). We have used a second order polynomial equation to capture the expected non-linearity in this relationship.

Regressions of energy capture, as a function of the temperature differential between the compost vapor stream pre-heat exchanger and the water in the HST were highly significant ($R^2 > 0.96$) for all 17 trials, but equation coefficients differed. Plotting all equations for the range of differentials in each trial on a single set of axes reveals consistent offsets among different trials (Fig. 6).

Trials starting with the highest temperature differentials were offset by those starting at a lower differential. As the differential increased, so did the energy recovery rate. This is important from an operational perspective, as the energy recovery rate decreased substantially as the temperature of the HST increased. Consequently, composting operations with large hot water demands may benefit by having multiple HSTs, where water is removed from the primary tank once it attains a target temperature, only to be refilled by well water.

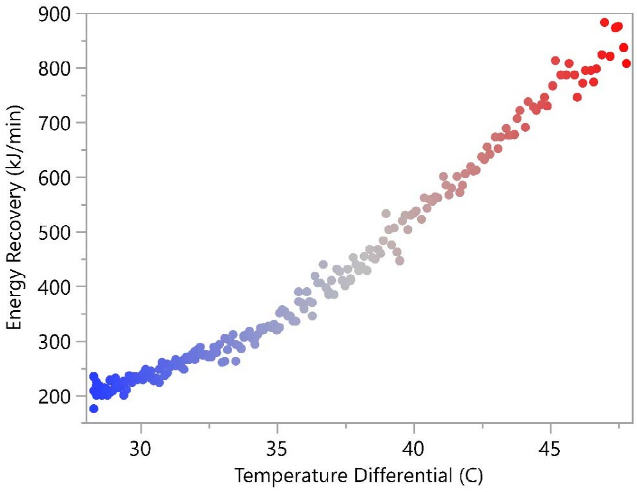

Fig. 5. Energy gain vs. temperature differential. Energy gain measured by increases in temperature in the heat sink tank (HST) as a function of the difference in temperatures between the vapor stream and the water in the HST.

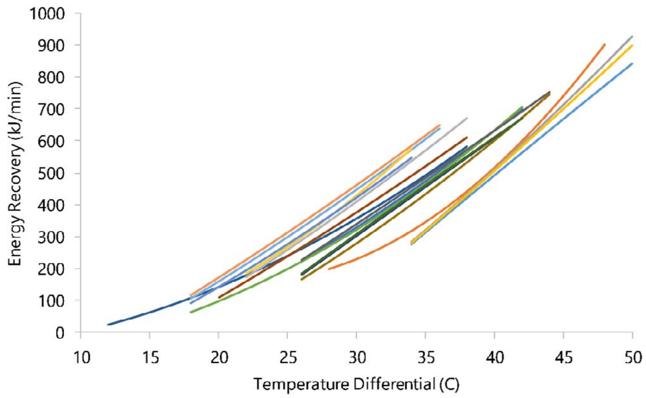

Fig. 6. Compost energy capture vs. temperature differential for 17 trials. Lines created using the coefficients for each trial. Each line is constrained within the actual temperature differentials measured during that trial.

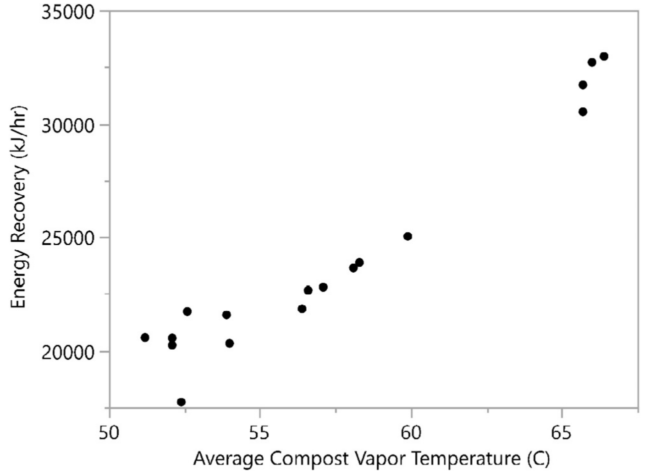

Fig. 7. Energy recovery rate by average compost vapor temperature for 17 trial runs.

When comparing the overall rates of energy recovery across the 17 trial runs, they were highly dependent on the incoming compost vapor temperature ($R^2 = 0.94$, $P < .0001$). Energy capture ranged from 17,700 to 32,940 kJ/h, with a compost vapor temperature range of 51–66 °C (Fig. 7).

These results are the first to present a range in energy recovery based on incoming compost vapor temperature for a commercial scale CHRS. This is important, as previous systems reviewed in Smith et al.

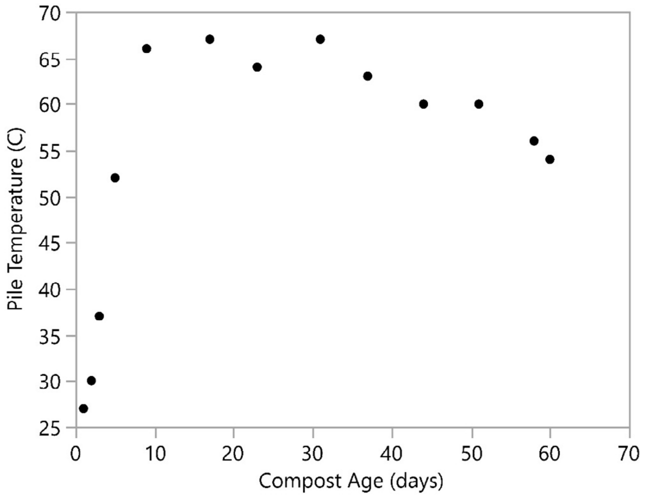

Fig. 8. Compost pile temperature over time for experimental batch 22.

[2], only presented energy recovery from the highest heat phase of the composting process. This does not consider the warmup and cooldown phases that exist during the composting process, or composting batches that are managed at lower temperatures. Fig. 8 displays a typical compost temperature vs. compost age curve for the facility in the present study.

For each composting batch, an initial temperature time lag occurs between the time when feedstocks are loaded and when they reach the minimum temperature for viable energy recovery (≥50 °C). Even without energy recovery, compost operators try and minimize this startup phase, as it effects overall composting throughput. However, the addition of energy recovery provides even further reason to carefully ensure a proper composting mix and microbial environment, as energy recovery rates suffer when operating at lower temperatures during this startup (Fig. 7). Furthermore, the way most composting systems with aeration are designed (individual pipes from each bay leading to a central manifold), means cooler compost vapor from new batches has the potential to cool down the aeration manifold and effect heat recovery on subsequent higher-heat batches in the aeration cycle. This potential cool down may warrant future composting operations interested in energy recovery to design unique aeration systems, where new batches can still be aerated, but have the vapor bypass the heat exchanger and primary manifold.

The issue of reducing energy recovery with cooler compost vapor is also present during later stages of the composting process. Following the initial high heat phase, compost pile and vapor temperatures gradually decline, as the easily digestible feedstocks are consumed by the microorganisms (Fig. 8). Eventually, the composting material will reach ambient temperatures, if given enough time [30]. While most commercial operations will cycle through composting batches prior to any substantial cool down, the range in energy recovery reported in Fig. 8 will allow future composting operators to more accurately model long-term energy recovery rates for their facilities, as they will be able to better account for energy recovery during the startup and cooldown periods based on their unique site characteristics. This will hopefully prevent future operators from overestimating energy recovery, which would occur if only utilizing recovery rates from the highest-heat phase.

3.3. Comparison with other studies

The energy recovery rate of 17,700–32,940 kJ/h reported in this study is difficult to compare to that of other commercial operations, as few systems exist, due to the novel nature of commercial-scale CHRSs. Additionally, tremendous variability exists among composting operations regarding the type of CHRS, scale of the operation, how energy is utilized, and how it is reported. Allain [17] described a conduction-based CHRS at a commercial-scale facility in New Brunswick Canada, which was designed to melt snow and ice from their compost covers during the winter season. The heat exchange system can recover 16,350–23,000 kJ/h. from 11,000 Mg of composting biosolids. The lower energy recovery rate from this operation is likely due to the type of heat recovery system, which is conduction-based. Smith et al. [2] found that these types of systems are less efficient than those recovering energy from compost vapor, as a majority of the energy within a composting pile is contained in the vapor stream.

Day [19] described a commercial-scale CHRS at the Hawk Ridge composting facility in Maine, USA, which processes 34,405 m^3 of municipal solid waste per year. The CHRS is a vapor-condensing exchanger contained within the facility's odor scrubber. As compost vapor passes through the odor scrubber, it warms water to 43 °C in a closed loop between the scrubber and a radiant floor heating system in a maintenance shop. In 2011, the system saved $10,000 over the winter season, equivalent to an average recovery rate of 116,000 kJ/h. The higher energy recovery rate from this operation in relation to the present study is likely due to feedstock volume, which is 12 times more than the UNH system. Furthermore, the actual heat exchanger is different, making comparisons difficult.

Even when comparing the recovery rates from the present study to other systems using an Agrilab CHRS, recovery rates vary. For example, Tucker [21], described Agrilab's first CHRS, which can recover 211,000 kJ/h, when composting dairy manure and bedding from 2000 heifers. The higher energy recovery rate from this system is primarily due to scale, as this operation recovers energy from 3 times the quantity of feedstock at any one time. The surface area of the shell and tube heat exchanger is also twice the size to that of the UNH system and the heat storage tank is 2.7 times the size [29]. These factors contribute to a higher energy recovery rate. A second Agrilab ASP system, installed at City Soil and Greenhouse in Boston MA, USA also reported higher energy recovery rates of 63,300 kJ/h, with a system capability of 295,415 kJ/h [18]. While this site uses ASP composting with an Agrilab heat exchanger, the actual heat recovery unit is a more compact and efficient unit than the system being used at UNH.

In reviewing the literature on commercial-scale CHRS, it is apparent that all the systems in use are customized specifically to the operation's scale, energy demand, and site-specific characteristics, making comparisons between systems at this early state in the industry difficult. This point was also made by Smith et al. [2], who conducted a detailed literature review on CHRS. In their review, they reported energy recovery rates of 1895 kJ/h (sd = 1609 kJ/h) for small lab and prototype systems, to 20,035 kJ/h (sd = 16,505 kJ/h) for pilot systems and 204,907 kJ/h (sd = 118,477 kJ/h) for commercial systems. The primary variables associated with the varying rates were heat exchanger type and facility scale.

3.4. Energy recovery vs. compost quality

Of the active non-modeled commercial systems reported in the literature, energy recovery from the composting process has been considered as a value-added benefit, but secondary to managing the system for maximum throughput or compost quality [2]. This is one of the primary reasons why a majority of the commercial CHRS recover energy from the vapor stream of ASP systems, as energy recovery does not affect compost quality. Furthermore, many commercial systems in operation, including the one in the present study, carefully control compost pile temperatures to prevent them from exceeding 65 °C, which is the point at which beneficial microorganisms begin to die off [30–32]. For this reason, the energy recovery rates reported in this study and others, may be slightly lower than the maximum energy recovery potential from composting feedstocks. Some composting operations with different management objectives may find it more economical to manage feedstocks at higher temperatures, possibly as high as 75 °C.

Facilities composting biosolids or municipal waste come to mind. Regardless, as more composting operations detail a range in energy recovery rates by compost temperature, like the present study, future facility operators will be able to more accurately model and predict the most economical balance of energy recovery and compost quality for their site.

4. Conclusions

ASP composting with energy recovery is a viable technology for rapid composting of organic wastes and for generating usable amounts of heat. The efficiency of energy capture varies strongly and predictably with the differential in temperature between the compost vapor stream and the HST. Rates of energy capture in this study were 17,700–32,940 kJ/h with compost vapor temperatures of 51–66 °C. A 5-day temperature lag time existed between compost pile formation, and when compost vapor temperatures were sufficiently high for energy recovery (≥50 °C). A second temperature time lag also existed during each aeration cycle, where incoming vapor temperatures immediately following exit from the compost pile were not yet reflective of what was reaching the heat exchanger, with the differential being 4.4 °C following the first minute of aeration and 1.3 °C following minute six. While these temperature lag times are consistent with composting systems using aeration, they reduce energy recovery potential. As such, operators of composting facilities considering energy recovery may have to reconsider aeration system design and aeration cycles, should maximum energy capture be a goal.

Acknowledgements

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.11.006.

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