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Heat Recovery from Composting: A Comprehensive Review of System Design, Recovery Rate, and Utilization

Matthew M. Smith [a], John D. Aber [a], and Robert Rynk [b]

[a]Department of Natural Resources, University of New Hampshire, Durham, New Hampshire; [b]Department of Agricultural Engineering Technology, SUNY Cobleskill, Cobleskill, New York

ABSTRACT

It has long been recognized that composting yields a large quantity of thermal energy, which is normally lost to the surrounding environment as heat. Efforts to recover this heat using compost heat recovery systems (CHRSs) have been sporadic. Literature on the subject is also disjointed. To summarize the research that has been conducted, the authors performed an extensive literature review, covering publications in scientific journals, trade magazines, books, theses, and published reports. A focus on CHRS design and heat recovery rates is presented. The review covers 45 CHRSs in 16 different countries, ranging from simple hotbeds used in China 2000 years ago, to advanced super-thermal conductor heat pipe systems in 2016. Heat recovery rates varied significantly, with no predictable trend among the 45 systems. Recovery rates averaged 1895 kJ/hr (1159 kJ/kg DM) for lab-scale systems, 20,035 kJ/hr (4302 kJ/kg DM) for pilot-scale systems, and 204,907 kJ/hr (7084 kJ/kg DM) for commercial systems.

Introduction

It has long been recognized that aerobic composting liberates a great deal of thermal energy, which is normally lost to the surrounding environment as heat. There have been many sporadic and varied efforts to capture this heat for positive use. Some efforts have been scientific, attempting to estimate the potential amount of energy available using compost heat recovery systems (CHRS), but most explorations have focused on developing CHRS for commercial or academic interest. The scale of these applications ranges from compost piles of a few cubic meters (Brown 2014) to large in-vessel composting facilities (Irvine, Lamont, and Antizar-Ladislao 2010; Tucker 2006; Winship et al. 2008). Many CHRS advances have been made through independent projects, carried out by enterprising individuals seeking inexpensive energy for their homes or farms.

The available literature on the topic is correspondingly varied. The authors reviewed over 45 publications representing scientific journals, professional trade publications, student theses, books, published reports, and articles in popular media. The body of peer-reviewed literature is modest and does not adequately tell the story of CHRS development. To tell that story, information must be gleaned from professional and popular publications. Fortunately, some independent projects have been documented, although typically in a manner that is difficult to characterize scientifically. Likewise, reports of commercial ventures often lack the information needed to make standard comparisons between various CHRS applications. Nevertheless, advances in CHRSs have been and continue to be made, largely at the applied level and predominately by a handful of practitioners. The purpose of this article is to present a comprehensive status report of CHRS technology and its expected development.

Composting Heat Recovery Principles and Applications

Heat recovery from composting can be considered in three stages: heat production, heat capture, and heat

CONTACT Matthew M. Smith ms7@wildcats.unh.edu Department of Natural Resources, University of New Hampshire, 56 College Road, Durham, NH 03824, USA.

utilization. These stages are highly interdependent. The ultimate energy available from a composting substrate is the same as that available from combustion of the substrate, which can be found in existing data or analysis, such as calorimetry. Composting falls far short of completely oxidizing the organic compounds and liberating the inherent energy. The actual amount of heat produced is determined by factors such as feedstock energy content, feedstock degradability, duration of composting, and the conditions prevailing during composting (e.g., moisture, temperature, substrate consistency, and particle size). Estimates of energy release vary with the feedstock and how investigators characterize the energy. A literature review of various compost feedstocks from Adams (2005) found the average heat production rate to be 19.44 MJ/kg dry matter (DM).

As decomposition liberates heat, the surrounding composting substrate and its air and water increase in temperature. In addition, some of the liquid water evaporates, creating water vapor. Thus, the heat liberated during composting essentially takes two forms: sensible heat (energy associated with an increase in temperature) and latent heat (energy associated with an increase in water vapor). The total energy of a substance is characterized by its enthalpy (h) in units of joules per gram (J/g) or kilojoules per kilogram (kJ/kg). Enthalpy accounts for both the sensible heat and latent heat of a mass of air.

As air moves through a composting substrate, either by passive or forced convection, it removes heat released during composting. The air gains sensible heat as it increases in temperature, and it gains latent heat as it increases in humidity. Overall, its enthalpy increases. The amount of energy (q) that air carries away depends on the change in enthalpy (Δh) and the mass flow rate of the air ($\dot{m}$). It can be calculated by equation 1,

$$Q = \dot{m}(\Delta h) = \dot{m}(h_2 - h_1) \qquad \text{eq.}(1)$$

in which h_1 = the enthalpy of the air entering the system (e.g., ambient air), and h_2 = the enthalpy of the air leaving the system.

In a typical composting situation, the increase in enthalpy is predominately due to the increase in latent heat. For example, assume that ambient air at 20°C and 80% relative humidity moves through a composting substrate and exits at 50°C and 99% relative humidity. These conditions are realistic and representative of composting conditions generally (e.g., exiting air is commonly saturated with moisture). The enthalpy of the ambient air (h_1) is about 50 kJ/kg da and the enthalpy of the exiting air (h_2) is about 272 kJ/kg da. The difference, 222 kJ/kg-da, is the specific amount of composting heat removed by the air. The portion due to an increase in latent heat is 192 kJ/kg-da, or 86%. As this example suggests, water vapor is the dominant pool of heat available from composting.

There are three approaches used to extract heat from composting. The simplest method is direct heat utilization of compost vapor (Aquatias 1913; Fulford 1986). Greenhouses are the iconic use for these systems, as they can benefit from both the heat and carbon dioxide (CO_2) available in the composting exhaust air. The second approach is hydronic heating through conduction of within-pile heat exchangers (Brown 2014; Pain and Pain 1972). These systems can direct the heated water into a hydronic space heating system or use the heated water for a consumptive water use (e.g., equipment cleaning). Often, a storage tank is included to buffer temperatures and energy demand. The third and more recent approach is to capture the latent heat using compost vapor and a condenser-type heat exchanger (Brown 2015; Smith and Aber 2014; Tucker 2006). This approach captures the greatest quantity of thermal energy and is most commonly used by commercial composting sites.

The efficiency of the various heat recovery systems depends on the flow rate and temperature of the heat-extracting fluid. In general, greater flow rates and lower entering fluid temperatures capture more heat, but exiting fluid temperatures tend to decrease. To a large extent, the system flow rates and temperatures are tied to the utilization of the recovered heat. With CHRS that circulate water in pipes within a pile, the water flow rate is usually designed to yield a target exiting water temperature. At a given flow rate, more heat is extracted from the pile as the temperature of the return water decreases. Hence, the performance of the CHRS depends on the ultimate use of the energy and its affect upon the return water. For example, a system that consumes much of the heated water for cleaning equipment might return cold well water to the composting pile and thus extract a greater amount of heat. It is possible to remove too much heat, and consequently lower the composting temperature by circulating too much cold water (Brown 2014; Viel et al. 1987). For CHRS that recover heat from the exhaust air, the flow rate of the air is usually determined by the process aeration needs. The entering air temperature is determined by ambient conditions. Again, the efficiency of the CHRS depends on how heat is recovered downstream. The energy in the exhaust air can be wasted if a greenhouse is already warm or if the temperature differential in a heat exchanger is small because the heat is poorly used.

History of Compost Heat Recovery

While it is unknown when humans first began to utilize the heat from decomposing organic matter, it is known that rural farmers in northern China were capturing this renewable heat source over 2000 years ago, with the use of hotbeds (Brown 2014). This CHRS was constructed by digging a 1 m trench, filling it with manure, and covering it with a layer of topsoil for crop production. When planted above the decomposing manure, plants benefited from the microbially-produced heat being generated below, allowing for season extension of 1–2 months in the spring and fall.

Extracting heat from compost was further refined in France, starting in the 1600s, where hectares of glass-enclosed hotbeds were utilized for winter cultivation and season extension (Fulford 1983). During this period, the most commonly used feedstock was horse manure. A mixture of old and fresh horse manure was used to balance the heat released. Too much fresh manure would create temperatures too hot for optimal plant growth, while too much old manure would not produce enough heat (Aquatias 1913). The glass-enclosed French hotbeds also required less manure than the hotbeds used in China. Aquatias (1913) described using only a depth of 25.4 cm of compost when compacted, or 30.5 cm–33 cm when using loose manure. Depths beyond 33 cm created too much heat, causing leggy plants in the winter from an uneven ratio of favorable heat to unfavorable light levels. This heat recovery method was suitable for growing winter crops capable of handling soil temperatures below 10°C–13°C. Large-scale use of French hotbeds came to an end in the 1920s, as the horse was replaced with the automobile. With the primary composting feedstock (horse manure) not being as abundant, large-scale use of this CHRS disappeared (Fulford 1983).

From the 1940s to the 1970s, a similar method of direct heat utilization from composting rose to popularity with Dutch and English farmers. Instead of using horse manure in glass-enclosed trenches, decomposing straw bales were used as the heat source and growing medium (Loughton 1977). Straw bale culture involved soaking bales with nutrient-rich liquid manure, capping them with compost, and then planting crops on top. The heat and CO_2 from the decomposing straw were commonly used for season extension of tomatoes, cucumbers, and lettuce. Loughton (1977) reported a 21% increase in yield for spring-grown cucumbers on bales, when compared to those grown in the soil. He also reported that wheat straw was the best medium for heat production, while hay bales had poor results. This heat recovery method lost favor, due to the high cost of straw (Fulford 1983).

Modern Era Begins 1971–80

CHRSs made a significant leap forward, with the publication of Pain and Pain (1972). This book described the work of Jean Pain and his combined heat and power composting system in France. Prior to this work, the thermal energy from composting was primarily recovered passively via convection of heat to the root zone of crops. Jean Pain's system, called a Pain mound, was very different, utilizing a 50 Mg heap of chipped brushwood with hundreds of meters of water-filled tubing imbedded in the compost for heat exchange. The decomposing brushwood warmed water within the tubing via conduction. The ability to warm water significantly increased the utility of the CHRS, as it could be used for more than just agricultural purposes. Pain and Pain (1972) reported that a 50 Mg heap of brushwood warmed well water from 10°C to 60°C at a rate of 4 liters per minute for 6 months, without interfering with the composting process. The system supplied domestic hot water and heating to a 100 m^2 farmhouse for 6 months, by circulating hot water from within the composting mass to a cast iron heater. When looking at heat recovery, the system was capable of extracting 50,115 kJ/hr or 4330 kJ/kg DM over a 6-month period. In addition to using compost heat for the farmstead, the authors described using a mound with 16,800 kg of feedstock to heat a 105 m^2 (211 m^3) high tunnel. The authors reported that they were capable of growing fruits and vegetables in spring-like conditions during the winter season.

A second type of CHRS was described in Knapp (1978). The system was similar to that of the French hotbed, only it used a 7.6 m^3 pile of decomposing leaves, household waste, lawn clippings, and manure within a greenhouse for winter heating. During the 30-day trial, it was found that compost vapor emitting from the pile provided frost protection against killing frosts, due to a thin layer of hoarfrost that formed on the plants. Knapp (1978) was able to grow onions, garlic, Bibb lettuce, corn-salad, chervil, cabbage, parsley, and rooted cuttings from shrubs, despite greenhouse temperatures dropping to −7°C four times during the testing period.

Another CHRS from this period was described by Vemmelund and Berthelsen (1979). Their system used a small-scale, double-walled 1 m^3 bin to process agricultural manures. Heat exchange occurred by filling the inner void between the bin walls with water, which was warmed via conduction from manures being aerated within the bin. A single bin was capable of warming water to 40°C, with a heat recovery rate of 2304 kJ/hr and a power efficiency of 4.5. The authors suggested that a combined 4-bin system, with inner heat exchange walls at the cross sections, would be capable of producing water at 50°C, as heat exchange would occur in the inner and hottest portions of the pile. The water could then be used directly in a radiator.

1981–90

From 1981–90, many CHRS designs evolved from conduction-based recovery systems to those using the compost vapor stream to capture the latent heat. Replicated research and peer-reviewed publications on the topic also started to appear in the literature. A primary reason for the increased interest in extracting heat from composting was due to the volatile energy prices that occurred during the previous decade, with the oil crises of 1973 and 1979. Authors of compost heat recovery work described the need to move away from volatile energy inputs and switch to more renewable forms (Fulford 1983, 1986; Haug 1993; Thostrup 1985).

In 1981, the Biothermal Energy Center (BTEC) formed in Portland, Maine, USA, with the mission of developing small-scale composting greenhouses (Fulford 1983). The organization had a series of publications detailing how to extract heat from composting. In one of those publications, White (1982) detailed how 0.6 m^2–2.2 m^2 of commercial greenhouse space can be heated with 0.9 Mg of externally located compost, if using recirculating water in EPDM heat exchange mats. It was also reported that EPDM heat exchange mats are more efficient at transferring compost heat than PVC, copper, or polyethylene.

Schuchardt (1984) took the same BTEC concept and applied it to a large-scale greenhouse in Germany. The system heated a 110 m^2 greenhouse by recirculating water through 2550 m of tubing contained within a 197 m^3 pile of chipped brushwood. Water temperatures within the tubing were maintained between 30°C–40°C for 9 months (February–October), while the central core of the compost pile remained at 60°C for 20 months. The experiment was cut short, due to compost settling that damaged the exchange tubing. Over the 9-month period, the heat recovery rate was 12,222 kJ/hr (2286 kJ/kg DM), saving 3140 L of heating oil and producing 140 m^3 of finished compost. The system had a coefficient of performance (COP) of 6.37.

During 1981–90, small-scale lab experiments were also conducted to determine the most effective methods of extracting heat from the composting process. Viel and colleagues (1987) used a water jacket around a 100 L insulated composting reactor containing sewage sludge, floating foams, and poplar sawdust to recover 628 kJ/kg–837 kJ/kg DM within the first 50 hours of composting. The energy used for aeration and mixing was roughly 1256 kJ/kg DM, resulting in a negative COP. The authors also found that fats were almost completely degraded (85%), indicating that they were capable of providing much of the thermal energy release. They also found that extracting heat too early through the exchange tubing impaired microbial activity by suppressing the temperature. If heat recovery was delayed until compost temperatures reached 60°C, microbial activity would increase after activating the heat exchanger. Seki (1989) and Verougstraete, Nyns, and Naveau (1985) reported a similar finding, where utilization of heat during the composting startup phase (4 to 5 days) could inhibit microbial activity and reduce compost temperatures if using a within-pile heat exchanger.

Verougstraete and colleagues (1985) found that within-pile piping systems limit energy recovery potential, due to the poor heat conduction of cellulosic substances found in compost. Heat exchange tubing is also difficult to install and fix once placed in the pile. The authors recommended recovering heat from compost vapor, using an air-to-water heat exchanger.

Issues concerning within-compost heat exchangers were also described by Thostrup (1985), after testing three different compost heat extraction methods in Denmark. In the first experiment, pig manure was placed in an insulated composting chamber, surrounded by a heat exchange water jacket. This system was not capable of producing water above 40°C, and the compost could not be mixed, due to the location of the heat exchange unit. The second heat extraction method directed exhaust vapor from a forced aeration composting system into an air-to-water heat exchanger. This method had positive results, capable of warming water to 55°C. This design was applied to a pilot-scale composting plant, processing manure and bedding waste from 200 pigs and 35 sows. The system was a tower design, where compost vapor was forced through a chamber containing heat exchange pipes with a working fluid. Over the 21-day test period, 5 m^3 of compost was capable of producing 16,925 kJ/hr, with a system COP of 6. The pilot plant was mechanically complicated and was taken offline after 6 months, due to high labor costs (Thostrup 1985).

Fulford (1986) described a viable greenhouse CHRS that successfully utilized heat from compost vapor for winter crop production. The CHRS was a joint effort between BTEC and the New Alchemy Institute. The system used a polyethylene-covered greenhouse with a 19 m^3 composting chamber attached to the north end of the structure. The composting chamber contained 10 separate bins, which were aerated by electric blowers that pushed air through the compost. The heated exhaust was blown through perforated pipe below growing beds, which served as biofilters. Heat transfer was direct utilization of the exhaust vapor from the composting chamber to the root zone of crops growing above the filter media. Heat was transferred to the media through stored latent heat (Fulford 1986). To ensure a constant supply of hot air, fresh compost was loaded into two composting bins every 4 to 5 days. When compost temperatures averaged 54°C, the upper growing bed was maintained at 24°C–27°C, while the temperature of the lower growing bed was maintained at 16°C. The compost-heated growing beds proved to be ideal for starting new seedlings.

In addition to supplying heat for growing crops, Fulford (1986) reported additional benefits of the compost vapor, which included irrigation, supplemental CO_2, and nitrogen fertilizer from ammonia (NH_3) that was converted to ammonium (NH_4^+) and nitrate (NO_3^-) in the biofilter media. The fertilization benefits of the NH_3 in the vapor stream were limited. A follow-up report from Schonbeck (1989) described the problem of excessive NH_3 accumulation in the soil. Excess nitrogen, combined with low light levels during the winter, also resulted in unhealthy NO_3^- accumulation in the leafy vegetables. A peat moss biofilter installed in the composting chamber was used to fix the problem, scrubbing over 90% of the NH_3 from the vapor stream prior to being sent through the growing beds.

1991–2000

While the heat recovery systems of this decade expanded on past technologies, the increased activity of peer-reviewed literature helped confirm many findings reported from independent organizations and individuals. Beck and colleagues (1992) described a CHRS that used the Carboferm® process, where liquid from an odor-removing jet washer was used for heat and nutrient recovery. The system operated by pulling air through compost in a concrete bunker, and sending it into a scrubber, where the condensing compost vapor exchanged thermal energy and nutrients to the process liquid. A heat exchanger was used to extract the thermal energy from the liquid, which was later used as a nitrogen fertilizer source for a greenhouse. The authors reported a 20% increase in crop production and a 20% savings in energy from using the stored latent heat at night.

A second study from Jaccard and colleagues (1993) reported the findings from a pilot-scale CHRS in Switzerland. The composting plant was a continuous-fed reactor, where 0.5 m^3 of yard waste was loaded and unloaded into the reactor by two tangent screws. The yard waste was aerated with a blower from the top down. Heat recovery occurred through an air-water heat pump. Composting and heat recovery took place for only 5 days in the reactor, taking advantage of the highest temperature thermophilic stage. Heat recovery had a power of 1948 kJ/hr, with 80% coming from latent heat, 8% sensible heat, and 12% sensible heat in the extract material. The authors projected that doubling the reactor size from 0.5 m^3 to 1.0 m^3 would double the recovery rate to 3600 kJ/hr, while a 6 m^3 reactor, with a feeding rate of 10 kg/hr, would be capable of providing enough hot water for four middle-sized homes.

Over the course of this decade, peer-reviewed research verified the feasibility and utility of using compost heat directly in growing beds, supporting the findings in the non-academic literature from previous decades. Hong, Park, and Sohn (1997) conducted a study looking at the effects of composting on underground soil temperatures within a 55 m^2 greenhouse in Korea. The study was conducted by placing a mixture of cattle manure and rice hulls in three long trenches (60 cm H * 60 cm W * 8 m L), with plants growing in parallel rows. A 4 cm diameter pipe below each composting trench supplied forced air to speed up the decomposition process. Researchers found that heat from the compost greatly affected the temperature of the adjacent growing beds. During the months of January and February, underground soil temperatures in the greenhouse were maintained between 17.5°C–32.5°C, while outside underground temperatures were 6°C–11.9°C. The authors concluded that the CHRS was suitable for winter cultivation in a greenhouse. A similar study from Kostov and colleagues (1995) compared the growth and production of cucumbers in a 142 m^2 greenhouse in Bulgaria, using direct utilization of compost heat. Cucumbers were grown in trenches containing either a mixture of cattle manure and soil (control) or a nutrient-supplemented compost mixture of vine branches; flax residues; or grape prunings, husks, and seeds. During the study period, root zone temperatures of cucumbers growing over the compost were higher than the control, reaching 29.6°C. Compost treatments also had higher CO_2 and microbial biomass than treatments with just manure. Treatments with compost had fruit production 10 to 12 days earlier and had a yield 48%–79% greater than the control. Compost treatments also produced 40%–44% more profit than the control. The increased yield and profit was attributed to warmer soils from the compost, elevated CO_2, larger microbial biomass, and the supplemental nutrients added to the compost media.

In addition to pilot-scale experiments, Seki and Komori (1992, 1995) tested CHRS designs at the lab level. In Seki and Komori (1995), a small cylindrical compost container containing both a within-pile and vapor condenser heat exchanger were used to recover 16%–22% of the heat generated during the composting of a chicken manure, rice bran, and sawdust mixture. Over the 7 to 14 day period, 714 to 773 kJ/hr were recovered. The energy to run the composting system was higher than the energy recovered, due to poor insulation of the composting chamber and the large pressure drop of the passing fluid through the heat exchanger. The authors suggested that more insulation and larger heat exchange tubes would solve the issue.

A brief article in *BioCycle* magazine described an innovative system developed by an organic lawn care company in Omaha, Nebraska, USA (Anon 1991). This CHRS combined a geothermal, solar, and composting system to heat water. The integrated system began by warming city water from 8.3 to 12.7°C through a subterranean geothermal tank. The tempered water was then sent to a second water tank, which was heated another 11°C with a solar system. The warm water was then sent through tubing within a composting pile of leaf and yard waste, where it was heated another 10°C to a final temperature of 34°C. During the winter, when outside temperatures dropped to −27°C and a wind chill factor of −44°C, the water temperature of the integrated system remained at 33°C. This system corrected one of the flaws of within-pile CHRSs, where cold water circulating through the composting pile can reduce microbial activity and future compost temperatures. It was reported that the integrated system worked well in the winter, but only required the solar heater during the summer months.

A final CHRS reported during this period came from Greer and Diver (2000). In their organic vegetable production guide, they described how to recover heat from decomposing straw bales. They reported that 26.5 L of manure tea are required per 23 kg straw bale for optimal heat production. Following saturation, bales are composted for a short period and are capped with 15 cm of compost-based potting mix once temperatures drop below 43°C. At this time, root balls of transplants are planted on top of the decomposing bale, which benefit from CO_2 and heat release.

2001–10

The period of 2001–10 saw an expansion in compost heat recovery technologies, as small-scale and pilot demonstration projects were scaled up to the commercial level. A majority of the findings were reported in a combination of student theses and practitioner-oriented sources, with few peer-reviewed publications.

Of the three theses in this review, all focused on the feasibility of using a CHRS to support winter greenhouse production. Adams (2005) modeled the effects of a CHRS for winter heating in Vermont, USA, using compost thermal data from peer-reviewed journals, local weather data, and operational data from a local composting facility. His findings suggested that if heating a greenhouse with an internally located compost pile, and using the compost vapor directly, 27% of the greenhouse floor space would be needed for the compost pile, and up to 50% if accounting for compost handling and storage. A second thesis from Gilson (2009) looked at the feasibility of year-round crop production using a CHRS in Ontario Province, Canada. The author proposed using a within-pile heat exchanger made of coiled pipe that would circulate hot water between an externally located compost pile and cast-iron radiator panels located within a greenhouse. Cast-iron radiators were recommended, due to their inexpensive cost and the ability to find them at recycling facilities. The author also suggested the benefits of not having to scrub volatile organic compounds (VOCs) and NH_3 from the compost vapor stream, which is necessary when using a direct-vapor CHRS. A third thesis from Chambers (2009) described a CHRS using a 435 kg mixture of horse manure, sawdust, and woodchips within a 2046 L insulated chamber. Heat recovery occurred via a within-pile heat exchanger made from two arrays of PEX piping, which connected to a radiator panel inside a winter high tunnel. The CHRS increased high tunnel temperatures 2 to 3°C above the unheated control, recovering 451 kJ/hr (1584 kJ/kg DM) over the 25-day test period, with a mean COP of 6.8. The heat exchange unit cost $2647 (real value adjusted for inflation).

One of the first large-scale commercial CHRSs was described in Tucker (2006). The system at Diamond Hill Custom Heifers in Vermont, USA, processes 544 to 726 Mg of agricultural wastes at any one time, using the aerated static pile (ASP) composting method. A suction fan pulls air through the compost into a network of pipes and into Agrilab Technologies heat exchange system. The system uses Isobar™ stainless steel super-thermal conductor heat pipes, which transfer the latent heat from the compost vapor to an 800 gallon tank of water. Heated water is used for warming milk formula and to provide radiant floor heating in the calf barn. Heat recovery rates of up to 211,011 kJ/hr were reported. Total project costs for the composting facility, storage barn, compost mixer, and Agrilab's heat exchange unit were under $500,000 (Smith 2016).

A second commercial-sized CHRS was described in Allain (2007). This CHRS was designed to prevent snow and ice from freezing GORE™ compost covers to the ground at a biosolids composting facility in New Brunswick, Canada. The system contained a network of pipes cast into the concrete composting pad, with a recirculating water/glycol solution. Central pipes under the middle of the compost windrows warmed the heat exchange fluid, which was then pumped to the outer pipes at the edges of the pile, warming the pad and preventing the GORE™ covers from freezing to the ground. The author found that if the heated fluid was pumped too frequently, compost pile temperatures decreased. A pump interval with 4 to 6 hrs of downtime per cycle allowed the heat exchange fluid to reach maximum temperature, while not affecting compost pile temperatures, due to heat exchange. A heat recovery rate of 16,353 to 23,000 kJ/hr for a 6 hr and 4 hr time off interval were reported, when using 11,000 Mg of compost at 60°C.

During this period, researchers also modeled how much heat could be extracted from commercial-sized CHRSs. In Winship and colleagues (2008), a transportable in-vessel composting container designed by Alpheco Composting in the UK was used to model heat production and recovery. The vessels, called Aergestors, had a stainless steel interior with a built-in aeration floor and irrigation system. Through a network of supply and exhaust manifold pipes, up to 10 vessels with a capacity of 15 Mg each could be grouped together with a single Aerator. Heat exchange would occur in the moisture trap of the Aerator, where a heat pump would be located. The heated water could then be tied into any building's hot water circuit. A second study from Irvine and colleagues (2010) used a commercial in-vessel composting operation in Scotland to model how much heat could be produced and captured from a CHRS. The proposed heat exchanger would be a network of water-filled stainless steel pipes hanging above the airspace in the composting vessel. Modeling suggested that 7000 to 10,000 kJ/kg DM could be obtained from the system over a 15-day period, warming water to 47.3°C–60°C at a cost of \$0.78/kWh for domestic hot water and \$0.16/kWh for space heating. A third study from Di Maria, Benavoli, and Zoppitelli (2008) used a model to simulate heat recovery from a proposed commercial ASP composting facility in Italy. The recovery system was a vapor compression heat pump that had heat transfer coils within the composting mass. The authors reported that the 55°C–65°C compost temperatures could be increased to 80°C–90°C with a heat pump, recovering 4000 to 5000 kJ/kg of thermal energy from the compost with a COP between 3.5–6.

2011–16

Since 2011, there has been significant growth in small-, medium-, and large-scale CHRS. Of the small-scale systems, Li, Yu, and Yu (2012) looked at developing a prototype CHRS that could be installed in U.S. households, utilizing waste from only the home for heating needs. The system was tested using a lab reactor with a mixture of grass clippings, sludge, leaves, and sawdust. The composting system used two chambers. One chamber contained 92.4 kg of feedstock, while the second contained a water tank and an air-to-water heat exchanger. A net energy generation of 4845 kJ/hr was recovered.

Gnanaraj (2012) used a small-scale lab reactor to test a CHRS in India, using 39.6 kg of sugarcane waste. A copper plate connected to a heat pipe transferred thermal energy from within the composting mass to an external heat exchanger with a water jacket for the heat sink. An average heat recovery rate of 1080 kJ/hr over 42 days was reported.

A third small-scale lab experiment was conducted by Seki, Kiyose, and Sakida (2014), to examine the ability of a CHRS to warm a fishpond for use in rural regions of Japan. The heat recovery system contained three separate containers, with the first being a 0.157 m^3 composting chamber of bamboo chips. A 0.9 m stainless steel water loop was imbedded in the compost to extract heat through conduction and was connected to a 0.0156 m^3 water reservoir through a closed loop. Warm water from the reservoir was circulated through a third container (0.0156 m^3) serving as a fishpond through a 2 m loop of copper pipe. Results from this experiment were input into a model to test the capability of a 50 m^3 bamboo chip pile to heat a 5 m^3 fishpond. Model simulations suggested that the CHRS could extract heat for 42 days and maintain the fishpond at 20°C.

In addition to small-scale lab experiments, several pilot-scale and mid-scale CHRSs were reported in the literature, with many of them being modified Jean Pain mounds. Two organizations, one American (Compost Power Network [CPN]) and the other German (Native Power), led the way in developing these CHRSs. Both organizations provide workshops and technical details on how to replicate these heat recovery systems. A book titled *The Compost-Powered Water Heater* from CPN founder, Gaelan Brown, details how to replicate CHRSs, including their modified Jean Pain mound, which is capable of recovering 10,550 kJ/hr (5081 to 7500 kJ/kg) from a 31 m^3 heap of woodchips over a 12- to 18-month period (Brown 2014). The material cost for the heat recovery components of a modified Pain mound is roughly \$1000 (Brown pers. comm. 2016).

A second type of mid-scale CHRS was described in Alwell (2014). This system contained four composting bins, with a combined feedstock capacity of 5 m^3. Bins were made of dimensional lumber, foam board insulation, and PVC pipe. Each bin was aerated from below using a blower and was connected to a 1041 L tote of water, which served as a heat sink for two separate heat exchangers. The first heat exchanger was a stainless steel tube within the compost pile, while the second was an array of copper pipes located within the exhaust line of the system. Heated water was sent to growing beds within a high tunnel through an underground PEX pipe. Over a 5-day period, a 28 m^2 growing bed within a high tunnel was warmed 3°C, saving 20 L of propane (4023 kJ/hr). The cost of the CHRS was \$7000, with a majority coming from the 140 W solar panel used to run the pumps and blower.

Another mid-scale CHRS was described in Brown (2014). The system was installed on a dairy farm in Vermont, USA, to process agricultural wastes. The system used a rectangular insulated composting box (3.7 m *3 m *12.8 m) built over a concrete aeration floor. Heat was recovered by blowing air through the compost and up into the ceiling, where 366 m of polyethylene tubing were attached. Water was circulated between the tubing and a radiator in an adjacent 149 m^2 workshop. The system captured 21,101 to 31,652 kJ/hr continuously.

In addition to small- and mid-scale CHRSs, there was continued reporting on commercial-sized systems in the literature. Rada and colleagues (2014) described a proposed large-scale CHRS that would be designed to dry sewage sludge with heat generated from an adjacent food and green waste composting facility. The goal would be to reduce the volume and weight of the sludge and increase the ease of storage before further processing. The proposed composting plant would be a collection of concrete bio-cells with an aeration floor cast into the concrete, and a stainless steel heat exchange tube in the upper portion of each unit. Exhaust gas would warm water in the heat exchanger through conduction and convection. The heated water would then be circulated through tubing in the pad below the sludge, promoting evaporation. Modeling suggested that a composting plant with six biocells and an annual feedstock capacity of 15,000 Mg would have a heat recovery power of 153,000 kJ/hr.

Day (2014) described an active commercial-scale CHRS at the Hawk Ridge composting facility in Maine, USA, which processes over 34,405 m^3 of municipal solid waste per year. The facility, which is operated by Casella Organics, uses a geothermal heat pump and a CHRS in a hybrid geo/biothermal system. During winter, hot compost vapor passing through the facility's odor scrubber warms process water to 43°C. The heated water is then sent through underground piping to warm a maintenance shop through radiant floor heating. It also warms an office building by warming the soil around an existing geothermal heat pump. System cost was $40,000, with an annual energy savings of $10,000 per year.

During this period, Triea Technologies™ also began selling and refining their commercial-scale CHRS called the BioMASS HRS™. The system is marketed for the poultry industry, where the heat is used to warm chicken houses. Initially, their test facility in West Virginia, USA, extracted heat from a closed water loop between a heat exchanger in the compost and a heat pump. The heated fluid was then sent to a fluid-to-air heat exchanger in another closed loop, warming fresh air to 37°C for the poultry house. Energy recovery rates of 153,862 kJ/hr (4294 kJ/kg DM) over a 50-day period were reported. The company converted their CHRS from a within-pile conduction system to an exhaust vapor condenser to increase heat recovery. The new system has a peak recovery output of 395,646 kJ/hr (11,041 kJ/kg DM), when composting 184 m^3 of poultry manure and bedding over a 50-day period (Triea pers. comm. 2015).

Significant expansion and advances were also made in the commercial-scale CHRSs sold by Agrilab Technologies, with four systems becoming operational during this time period. As with their first system described earlier in Tucker (2006), all four CHRSs use the ASP composting method with one of Agrilab's vapor condensing systems. The first system from this time period was installed at Sunset View Farm in New York, USA, becoming fully operational in early 2011. The farm raises 2000 heifers and composts cow manure and bedding. Water temperature in the heat sink tank is maintained at 46°C, representing an average heat recovery rate of 205,736 kJ/hr and a farm energy savings of $9285 (Quinn, Quinn, and Jerose 2014).

In 2012, Agrilab installed a smaller-scale CHRS at Jasper Hill Farm in Vermont, USA. Heat recovery comes from composting manure solids and bedding from the 45-head cow barn, while liquid manure, whey from their cheese-making facility, and wash water are used in the anaerobic digester. The heat from the CHRS is used to warm three 26,500 L anaerobic digester tanks and maintain temperatures at 38°C (Smith 2016). The 27 to 32°C compost exhaust vapor post heat exchange is used in their winter greenhouse beds, which serve as a biofilter. They are growing tomatoes, peppers, greens, strawberries, pineapples, and a banana tree (Brown 2014). The total system cost for the commercial-scale composting facility, anaerobic digestion system, heat recovery unit, and feedstock storage area was under $750,000 (Smith 2016).

In 2013, a third Agrilab CHRS was installed at the University of New Hampshire's Organic Dairy Research Farm in New Hampshire, USA. The system, described in Smith and Aber (2014), was designed specifically for research trials on compost heat production, recovery, and utilization. The CHRS is similar in size to Jasper Hill's, processing manure and bedding waste from a 100-head dairy herd, but the aeration lines on the main composting floor were designed in pairs, allowing for replicated research on compost batches. The heated water is also used in the milk room for cleaning and sanitizing equipment. A detailed analysis outlining the cost structure and how to replicate the system for under $300,000 is described in Smith (2016) and Smith and Aber (2014).

In 2015, a fourth Agrilab system was installed in the urban environment of Boston, MA, USA. The composting site, operated by City Soil & Greenhouse LLC, uses a mobile Agrilab system (The Compost Heat Wagon™) contained within a portable trailer. The portable unit serves as the heat recovery and aeration source for a 260 m^2 composting greenhouse. The composting greenhouse has a 191 m^3 capacity composting floor with an integrated biofilter and growing bed system. Heated water from Agrilab's system is used for radiant heating in the growing beds, allowing for year-round crop production. Heat recovery rates of 63,300 kJ/hr have been recognized, with a system capability of 295,415 kJ/hr (Brown 2015).

Concluding Thoughts

This review covered 45 different CHRSs in 16 different countries, from simple systems used by Chinese farmers 2000 years ago, to advanced systems using super-thermal conductor heat pipes in 2016. A wide variation in project scale was presented, with 11 lab-scale, 19 pilot-scale, and 15 commercial-scale systems described. The 11 lab-scale CHRSs were all reported in peer-reviewed literature. This was in contrast to the literature from the nine commercial-scale systems using operational data, which were all published in practitioner-based sources or conference proceedings. The lack of peer-reviewed literature using actual and not modeled data for commercial systems represents a significant research gap that must be filled.

CHRSs fit into four broad categories, based on how the thermal energy was extracted. The categories include direct heat utilization of compost vapor (nine systems), hydronic heating through conduction of within-pile heat exchangers (17 systems), compost vapor exchange through latent heat (17 systems), and a combination of several technologies (two systems). While direct vapor and within-pile CHRSs are still being used today, academic and practitioner-based literature indicated preference toward systems extracting heat from compost vapor using condenser-type heat exchangers. Reasons provided for using compost vapor heat exchangers over within-pile exchangers were as follows:

1. (1) Within pile heat exchange tubing can be easily damaged, due to compression from compost settling, loading, or unloading (Pain and Pain 1972; Schuchardt 1984).
2. (2) Recirculating the within-pile heat exchange liquid too early or too fast can inhibit the composting process, reducing temperatures and future heat exchange (Allain 2007; Seki 1989; Viel et al. 1987; Verougstraete et al. 1985).
3. (3) Compost cannot be mixed once the heat exchanger is placed within the pile (Thostrup 1985).
4. (4) Energy recovery is limited due to poor heat conduction characteristics of composting feedstocks (Verougstraete et al. 1985).
5. (5) Unlike the within-pile approach, vapor heat exchangers can potentially capture the abundant latent heat energy produced during composting (Jaccard et al. 1993; Verougstraete et al. 1985).

Preference for vapor exchange was also shown by active commercial sites covered in this review, with 87% of the facilities using that form of heat exchange.

When looking at the heat recovery capabilities of the 45 CHRSs, no predictable trend of heat recovery by system type or scale was apparent. Recovery rates were 1895 kJ/hr ($s = 1609$ kJ/hr) for lab-scale systems, 20,035 kJ/hr ($s = 16{,}505$ kJ/hr) for pilot-scale systems, and 204,907 kJ/hr ($s = 118{,}477$ kJ/hr) for commercial-scale systems. On an energy-per-weight basis, recovery rates were 1159 kJ/kg DM ($s = 602$ kJ/kg DM) for lab-scale systems, 4302 kJ/kg DM ($s = 2003$ kJ/kg) for pilot-scale systems, and 7084 kJ/kg DM ($s = 3272$ kJ/kg DM) for commercial-scale systems. Heat recovery rates varied significantly and were dependent on a combination of the following factors: system scale, type of heat exchange system, composting method, composting feedstocks, continuous versus batch loading, model versus operational data, geographic location, duration of heat recovery, and method of reporting thermal energy recovery. An attempt to standardize the reported recovery values to a single comparable unit of heat recovery per unit dry biomass was attempted but proved to be impossible. A majority of the literature from practitioner-based sources reported values as BTU/hr and did not provide information on how much biomass was used to generate the energy recovery values. If information on biomass quantity was reported, moisture content values were absent, making it impossible to calculate dry biomass without making assumptions. Complicating the standardization process further, commercial systems like those from Agrilab Technologies reported recovery rates from active facilities using batch loading, where various ages of compost contributed to the recovery value. As a consequence, the 211,011 kJ/hr value reported in Tucker (2006) underestimates the maximum recovery from the system, as several compost batches in the facility were older and had passed the high-heat active phase. This method of reporting also made it difficult to convert to a heat recovery-per-unit weight value, as the value would include large quantities of biomass not contributing significant quantities of heat.

For CHRS data to be more comparable, recovery rates should be presented as heat recovery per unit time and as specific energy, describing energy per unit mass (kJ/kg DM) or per unit of volatile solids (kJ/kg VS). Both of these values should also be presented as net energy recovery, removing the energy required to run the CHRS. Of the 45 systems reviewed, only eight provided net efficiency, making it difficult to truly compare systems. Further, it is also necessary to report whether average or peak recovery values are being used and for the duration those values represent. This is especially important due to the changing temperatures found within a composting mass over time. If energy recovery is only reported during the thermophilic phase, recovery rates will be much higher than those reporting recovery rates over a several week or month period. By way of example, Jaccard and colleagues (1993) reported heat recovery over a 5-day period, while Schuchardt (1984) reported heat recovery over a 9-month period. Ideally, multiple heat recovery values would be reported, representing the various stages of the composting process. Importantly, this would provide compost practitioners more useful information on how much thermal energy they may be able to extract on their site based at their composting period.

In addition to specific energy, authors of compost heat recovery work should also specify the cost of their CHRS and the cost in relation to energy produced (kWh). Of the 45 systems reviewed, only eight detailed cost. Without an economic component, comparison between technologies becomes difficult. While some systems may boast high heat recovery rates, the actual cost per unit of energy may actually be higher than other compost heat recovery technologies.

While the 45 CHRSs described in this review show tremendous variability in heat recovery, design, and efficiency, the authors hope that the breadth of systems covered will help compost practitioners decide what type of system is best for their site. The significant increase in practitioner-based publications on CHRSs from 2010–16 also suggests an interest in this field of composting, especially with commercial-scale operations. This represents a distinct shift from pre-2011, which was dominated with prototype and lab-based systems, indicating that recovering heat from composting is becoming a viable alternative energy source and is that much closer to becoming a mainstream process.

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ORCID

Matthew M. Smith http://orcid.org/0000-0002-5641-2181
John D. Aber http://orcid.org/0000-0001-7262-526X
Robert Rynk http://orcid.org/0000-0003-4866-0537

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