Literature Review on Composting Heat Recovery

Rongfei Zhao, College of Water Conservancy, Shenyang Agricultural University, Shenyang, Liaoning, 110866, China
Huiqing Guo*, Department of Mechanical Engineering, College of Engineering, University of Saskatchewan, Saskatoon, SK, S7N 5A9, Canada; Email: huiqing.guo@usask.ca
Wei Gao*, College of Engineering, Shenyang Agricultural University, Shenyang, Liaoning, 110866, China; Email: snowwei28@126.com
Guohong Tong, College of Water Conservancy, Shenyang Agricultural University, Shenyang, Liaoning, 110866, China

Written for presentation at the
CSBE/SCGAB 2015 Annual Conference
Delta Edmonton South Hotel, Edmonton, Alberta
5-8 July 2015

ABSTRACT The heat produced from solid waste composting has stimulated great interest in heat recovery and utilization. This review presented advances in the composting heat recovery research in the last decade. Results of various experimental and theoretical studies on composting heat utilization are summarized. The results show great potentials for utilizing heat produced by composting process. Common problems experienced by the current methods are how to realize the maximum heat recovery without negatively impacting compost quality and the economics of heat recovery methods. This study also gives details of the problems and research gaps. Further advancement of these methods is currently receiving increased interest, both academically and commercially.

Keywords: Composting, Solid waste, Heat recovery

INTRODUCTION

Composting is a significant bio-recycle process (Rynk, 2000). It would produce huge number of heat due to heat liberation from microbial metabolic activity. Elevated temperature of the order 70-90°C may be found within a few months or even a few days during the composting of municipal solid waste (MSW; Hogland et al., 1996). The temperature increases will lead approximately 85% of industrial waste to be combustible when heat-loss is unable to balance heat generation (Hogland et al., 1996). The heating-up during a composting process is determined by the degradability and energy content of the substrates (Nakasaki et al., 1985; Weppen et al., 2001), the availability of moisture and oxygen (Garcia and Mato, 1996; Richard et al., 2002; Arslan et al., 2011), the C/N ratio
(Nakasaki et al., 1992), the PH value (Dougherty, 1999), and the mode of energy conservation (Haug, 1993; Sundberg, 2004).

Conventional composting processes typically comprise four major microbiological phases in relation to temperature: mesophilic, thermophilic, cooling, and maturation, and the final product is compost (Haug, 1980). The composting processes must be suitably managed and the progressive changes with time of the physical and chemical parameters of the compost must be carefully controlled to give products with optimal qualities. Because compost quality is defined by its maturity and stability, and it is determined by quality of the feedstock materials and management of the composting process (Brinton et al., 1995; Butler et al., 2001; Gomez et al., 2006; Carballo et al., 2008).

In order to keep the optimized temperature and meet regulatory requirements for pathogen control, current composting approaches and technologies tend to take 55°C as the temperature to remove the most heat possible without lowering the temperature inside the bed under 55°C and while maintaining the appropriate aeration, and thereby shortening the composting process (MacGregor et al., 1981; EC, 2003; Neugebauer et al., 2014).

Hence, the objective of this study is to investigate composting processes related to heat recovery, such as optimal heat recovery temperature, potential energy, recovery models, recovery methods and research gaps.

**COMPOSTING MATERIALS**

There are three types of composting materials.

1. Bio-waste, such as biomass feedstock, municipal, industrial, and construction waste (Incer et al., 2003; Antizar et al., 2008). For example, the MSW contain 60% of biodegradable waste. It is clear proof of the importance of composting biodegradable MSW as well as its utilization for energy generation.

2. Waste from Livestock and poultry industry includes a mixture of excreta, bedding material or litter, waste feed and feathers removed from Livestock and poultry houses (Ahna et al., 2007; Tang et al., 2007).

3. Sewage sludge (SS), SS mixed with MSW can improve the structure and C/N of SS, increase the nitrogen content of MSW for the compost product, and meet the goal of fast sanitization (Chen et al., 1996; Marek et al., 2003; Banegas et al., 2007; Guardia et al., 2008).

**COMPOSTING HEAT**

*Composting temperature*

According to the composting temperature, there are two kinds of composting. One is thermophilic composting, it worked at the thermophilic temperatures higher than 45°C. The other is mesophilic composting which is carried out at mesophilic temperatures lower than 45°C (Mbah and Odili, 1998; Adler, 2005). The best temperature of these two kinds composting are shown in Table 1. It indicates that mesophilic composting at a lower temperature is more favorable for the decomposition of waste although a higher temperature is effective for the elimination of pathogenic and weed seed contaminants during composting (Grundy et al., 1998; Elorriota et al., 2003).

Temperatures should be maintained over 55°C for at least 15 days in thermophilic composting to destroy pathogens, weed seeds and fly larvae and temperatures over 65°C should be avoided to prevent immobilization of beneficial microorganisms and minimize the loss of N during composting (Rynk, 2000). The thermophilic phase of the process runs at considerably high temperatures (45-65°C). It keeps several days to 6 weeks, probably owing to the loss of easily degradable organic
matter, cooling of the heaps during mechanical turning, or a lack of moisture (below 50%) (Raclavška et al., 2011). The optimal moisture content for composting is 50-70% (Richard et al., 2002; Vergnoux et al., 2009). Extending this phase of the composting process may result in shortening the entire process and reducing the amount of harmful gases produced by it. The higher temperatures (70-80°C) can hygienize the compost, but waste of agricultural origin does not need hygienization. Therefore, the excess heat can be taken away and used in another place (Bari and Koenig, 2001; Ekinci et al., 2006; Lin, 2008).

### Table 1. Composting temperature

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Temperature phase</th>
<th>Best temperature (°C)</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suler et al.</td>
<td>1977</td>
<td>thermophilic</td>
<td>50-60</td>
<td></td>
</tr>
<tr>
<td>MacGregor et al.</td>
<td>1981</td>
<td>thermophilic</td>
<td>52-60</td>
<td></td>
</tr>
<tr>
<td>Nakasaki et al.</td>
<td>1985</td>
<td>thermophilic</td>
<td>50-60</td>
<td></td>
</tr>
<tr>
<td>Miller</td>
<td>1992</td>
<td>thermophilic</td>
<td>55-65</td>
<td></td>
</tr>
<tr>
<td>Palmisano and Barlaz</td>
<td>1996</td>
<td>thermophilic</td>
<td>55-59</td>
<td></td>
</tr>
<tr>
<td>Rao et al.</td>
<td>1996</td>
<td>Mesophilic</td>
<td>37</td>
<td>Maximal mineralization of poplar wood carbon to CO₂</td>
</tr>
<tr>
<td>Vikman et al.</td>
<td>2002</td>
<td>Mesophilic</td>
<td>35</td>
<td>Maximum carbon converted into microbial biomass carbon</td>
</tr>
<tr>
<td>Liang et al.</td>
<td>2003</td>
<td>Mesophilic</td>
<td>43</td>
<td>Greatest amount of cumulative O₂ uptake</td>
</tr>
</tbody>
</table>

### Heat production capacity

Composting has been described as the aerobic degradation of organic wastes where heat is released in the oxygen-consuming microbial metabolism (Sundberg, 2004). Data on the amount of heat produced during composting is scarce, and the results are as diverse as the composition of composted biomass. A limited number of studies have investigated the potential heat production of compost as given is Table 2.

### Table 2. The potential heat production of compost

<table>
<thead>
<tr>
<th>Author</th>
<th>Material</th>
<th>Year</th>
<th>Temperature phase</th>
<th>Heat production (MJ kg⁻¹)</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guljajew and Szapiro</td>
<td>agricultural waste</td>
<td>1962</td>
<td>whole</td>
<td>0.961</td>
<td>0.302-1.802</td>
<td></td>
</tr>
<tr>
<td>Stainforth</td>
<td>wheat straw</td>
<td>1979</td>
<td>whole</td>
<td>17.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sobel and Muck</td>
<td>wheat straw</td>
<td>1983</td>
<td>whole</td>
<td>12.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steppa</td>
<td>MSW</td>
<td>1988</td>
<td></td>
<td>9-11</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Ahn et al.</td>
<td>poultry manure and wood</td>
<td>2007</td>
<td>whole</td>
<td>16.83–19.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>shavings mixture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klejment</td>
<td>MSW</td>
<td>2008</td>
<td>high temperature phases (&gt;60°C)</td>
<td>1.136</td>
<td>1.136</td>
<td>1.136</td>
</tr>
<tr>
<td>Irvine et al.</td>
<td>industrial sludge</td>
<td>2010</td>
<td>whole</td>
<td>7-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bernstad and Cour</td>
<td>food waste</td>
<td>2012</td>
<td>lower heating value</td>
<td>1.7-6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lee et al.</td>
<td>livestock wastes</td>
<td>2014</td>
<td>whole</td>
<td>18.82</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Compost thermal conductivity coefficient**

The values of compost thermal conductivity coefficient are shown in Table 3. The value increases linearly with the compost temperature, moisture content and density (Ginkel, 1996; Kaleta, 1999; Klejment, 2008).

<table>
<thead>
<tr>
<th>Author</th>
<th>Material</th>
<th>Year</th>
<th>Moisture content (%)</th>
<th>Temperature (°C)</th>
<th>Density (kgm⁻³)</th>
<th>Compost thermal conductivity coefficient (Wm⁻¹K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ginkel</td>
<td>straw</td>
<td>1996</td>
<td>75</td>
<td>50-60</td>
<td>0.55-0.67</td>
<td></td>
</tr>
<tr>
<td>Kaleta</td>
<td>clover</td>
<td>1999</td>
<td>40</td>
<td>20-80</td>
<td>0.075-0.085</td>
<td></td>
</tr>
<tr>
<td>Klejment</td>
<td>MSW</td>
<td>2008</td>
<td>40</td>
<td>30-60</td>
<td>442-600</td>
<td>0.150-0.309</td>
</tr>
</tbody>
</table>

**Theoretical modeling**

Composting models supply a method to dynamically understand the heating-up and thermal balance process as a system (Haug, 1993; Mason, 2006). With simulation results, variations of different thermal balance components could be monitored during the whole composting process, instead of just giving an overall data that indicate which thermal balance component is significant.

Nelson et al. (2003) analyzed a spatially uniform model, based upon Semenovs theory for thermal explosions, for self-heating in compost piles. The singularity function (G) is

\[ G = \psi_b \exp[\theta] + (\psi_a \exp[\alpha_{\theta} - \theta])(1 + \beta \exp[\alpha_{\theta}]) \]  

Note that,

\[ G \psi_b = \exp[\theta] \neq 0 \]  

The model investigates the cases when self-heating is due to purely biological heat-release and due to a combination of biological and chemical heat-release. Since the system was described by a single (but non-linear), first-order ordinary differential equation, with few parameters, it is able to thoroughly investigate the generic steady-state behavior of the system when parameters are varied by using singularity theory (Golubitsky and Schaeffer, 1985). This model shows elevated temperatures can be accounted for by two mechanisms. However, it is not validated by experiment.

Sidhu et al. (2007) considered a two-dimensional, spatially-dependent model that contains both biological and chemical activity. The relevant equation for the model is

\[ (\rho C)_{eff} \frac{\partial T}{\partial t} = k_{eff} \nabla^2 T + Q_b(1-\varepsilon)\rho \exp[-\frac{E_c}{RT}] + Q_c(1-\varepsilon)\rho \exp[-\frac{E_c}{RT}] + \frac{A_1 \exp[-\frac{E_1}{RT}]}{1 + A_2 \exp[-\frac{E_2}{RT}]} \]
The formulation of this model is completed once the boundary conditions have been defined. The boundary conditions used in this study are specified in Figure 1, and are given explicitly below.

**Boundary conditions:**

\[ T = T_a \] along \( x = 0, \ x = L \) and \( y = h \)

\[ T = T_g \] or \( \frac{\partial T}{\partial n} = 0 \) along the base \( y = 0 \), \( (4) \)

**Initial conditions:**

\[ T = T_a \] \( (5) \)

The model incorporates the heat release due to biological activity within the pile and the heat release due to the oxidation of cellulosic materials. The heat release rate due to biological activity is modeled by a function which at sufficiently low temperatures is a monotonic increasing function of temperature. At higher temperatures, it is a monotonic decreasing function of temperature (Nelson et al., 2007). This functionality represents the fact that micro-organisms die or become dormant at high temperatures. The heat release due to the oxidation reaction is modeled by the usual manner using Arrhenius kinetics (Sidhu et al., 2007; Luangwilai et al., 2010). This model is validated by experiment. But, it does not consider oxygen consumption, and convection of oxygen into the pile.

Boniecki et al. (2013) analyze heat of the composting process of solid natural fertilizers with neural network modeling. Research highlighted the problem of neural prediction of heat processes accompanying the composting of selected natural fertilizers and focused on the estimation of lost heat generated as part of the exothermic reactions taking place during the process. The equation is

\[ q_r = q_w + q_k = 3.6UA(T_r - T_0) + \frac{VP}{X+1}(i_w - i) \] \( (6) \)

Research results showed that neural modeling can be effectively used in the process of estimating heat energy emitted and lost in the composting process. The model's analysis of sensitivity to input variables showed that the 6 most important parameters in the process of neural estimation of heat lost are (in the following order): \( T \) (temperature inside the bioreactor), SM (mineral substance mass), \( O_2 \) (% content of oxygen), \( V \) (stream volume), \( CO_2 \) (% content of carbon dioxide), and TIME (process duration).
Wang et al. (2014) developed a thermal balance model for composting process to determine variations of heat loss components (conduction, convection and latent heat loss) during the process. The thermal balance equation was

\[ (mc + m_Kc_R) \frac{dT}{dt} = E_{bio} - E_{con} - E_{wall} - E_{lat} \]  

Model results in this study show that the percentages of convective, conductive and latent heat losses of total heat loss varied significantly during the composting process. The peak percentages of conduction heat losses are 38.9 and 57.7% of total heat losses for the modeling situation with and without insulation, respectively. Substrate decomposition could significantly affect temperature changes and the whole thermal balance process.

HEAT RECOVERY METHODS

A limited number of experimental studies on compost heat recovery have been reported. One major problem during the study is the precision in controlling the processes of heat removal and aeration in the bed. Too much heat removal from a heap may result in a temperature drop inside it, which, in effect, can slow down (or even stop) the thermophilic phase of composting (Chroni et al., 2009). On the other side, too intensive aeration results in dessication of the composting material and the simultaneous loss of heat; and too little aeration slows down the composting process. The process control methods currently in use are usually based on adjusting the amount of air supplied to a compost heap by controlling either the temperature inside the bed or the oxygen content of the air which leaves the heap (Xiao et al., 2009). There are direct and indirect methods of heat recovery from composting.

1. Direct recovery method

A direct recovery method involves extracting heat from the material during the composting process.

Water heating

The first involves recirculating water through tubing buried within a compost pile or concrete slab. The systems using pipe buried within the pile are more suitable for backyard operations, where the time and labor consuming aspects of installing and removing the pipe during pile formation and breakdown, can be absorbed by an enthusiastic homeowner. This method is typically not suitable as a commercial practice where revenue is the goal, as it is labor/time intensive. Problems can also arise if too much heat is removed from the pile for the cold water. This scenario can inhibit microbial growth and crash the microbial population, causing putrid conditions.

A simple and efficient method of directly extracting heat energy from manure was pioneered by Pain et al. (2012) in which a litter pile is built in 10 inch thick layers with water tubes in between each layer. As air flows through the litter pile, the compost heat is transferred to the water in the tubes and then the tubes carry the heated water to a greenhouse as a source of radiant heat.

Lekic (2005) investigated the increase in water temperature between the inlet and the outlet of polyethylene pipes embedded in composting windrows and reports that 73% of the theoretical value of heat energy is transferred to the water. One main limitation of this study is the placement of the pipes within the compost mass. A solution proposed by Seki and Komori (1992) involved using a packed column heating tower that transfers the heat from the warm exhaust air of the compost to a volume of water.

Space heating

The second approach used to recover heat from a compost pile is to push (forced aeration) or pull (negative aeration) air through the pile. This is most commonly accomplished by placing compost on top of an aeration floor, where perforated PVC pipes are cast into concrete, covered by a perforated cover plate, which is then covered by 8” of woodchips. By mechanically moving air through the pile, the aerobic microbes receive needed oxygen, while excess heat is removed, both
of which allow for a larger and healthier microbial population (Rynk, 1992; Epstein, 2011). Heat recovery from a positive aeration system is one option, but has limited applications due to the difficulty in capturing the diffused heat across the pile. The amount of available heat is also limited, as only 13.4% of the heat generated within the pile is contained in the airflow (Themelis, 2005). Early research utilizing this technology came from the New Alchemy Institute, where a winter greenhouse was warmed through compost vapor, which had been sent through a biofilter (Fulford, 1986). Although limited to mostly horticultural applications, this method serves as a valuable tool for season extension and energy reduction for greenhouse and high tunnel growers in cooler climates.

2. Indirect recovery method

An indirect recovery method involves harvesting the heat indirectly by altering the form of the bio-waste material itself. Lee et al. (2014) reformed an advanced compost and energy system (ACES). In the ACES, technically, high water content in livestock wastes evaporate by an exothermal reaction caused from a specific group of aerobic fermentation microorganisms. The microorganisms produce heat higher than 80°C thus evaporating moisture retained in wastes. Livestock wastes and food wastes are comparatively tested. Resulting materials show relatively high caloric value and energy yield, 18.82 MJ kg⁻¹, in a heating value test.

Among many advantages of the ACES, a wastewater treatment process is not needed for the liquid separation from slurry waste. Rather, the ACES is more like a zero discharge system, not even using outer energy sources unlike conventional methods. By exothermic reaction, microorganisms heat out while digesting organic compounds of livestock waste. The temperature from the ACES is up to 80-90°C. With this heat, moisture inside of the waste is completely removed from a slurry waste, which other methods are not able to do. The ACES is not requiring any additional energy source to increase a heating value.

The biggest obstacle to convert livestock or food wastes to energy material is how to separate liquid from livestock waste and dispose of or treat the liquid part. The moisture content of livestock and food waste is up to 90%. If liquid out of this high slurry waste is appropriately managed, the remaining solid, as an organic mass, is apt to have a relatively high energy yield, such as 10.46-14.64 MJ kg⁻¹. In order to evaporate internal moisture out of high slurry waste, high energy demanding methods are conventionally used. In other words, it requires high costs to use electricity and gas for a liquid evaporation. In addition, it is time consuming to completely dry a slurry waste because moisture inside of the waste is not easily dried out. With this water content, a dried material is also odorous (Shin, 2002; Kim, 2012).

CONCLUSION

Recent researches have acquired many of achievements in the field of theory and experiment about heat recovery. Some heat recovery methods have been practiced in agricultural and industrial production. The potential energy content of poultry manure and wood shavings mixture composting is the highest, the values are range from 16.83 to 19.7 MJ kg⁻¹. Direct recovery method is the most used in the industrial composting due to its simplicity. The heat transfer calculation models normally could be used to simulate the specified composting process. There are many more to do for the heat recovery both in research and application, such as more simplified models for heating predictions of potential heat from composting, and high efficient heat recovery method.

LIST OF SYMBOLS

ψₙᵃ, Semenov number for the biomass
θ, non-dimensionalized bioreactor temperature,
ψₒ, semenov number for the oxidation of cellulosic materials
αₒ, dimensionalized activation energy for cellulose oxidation,
\( \beta \) maximum dimensionless rate of inhibition
\( \alpha_d \) dimensionless activation energy for the inhibition of biomass growth
\( (\rho C)_{eff} \) effective thermal capacity per unit volume of the bed (J m\(^{-3}\)K\(^{-1}\))
\( T \) temperature within the compost pile (K)
\( t \) time (s)
\( k_{eff} \) effective thermal conductivity of the bed (W m\(^{-1}\)K\(^{-1}\))
\( Q_c \) exothermicity for the oxidation of the cellulosic material (J kg\(^{-1}\))
\( \varepsilon \) void fraction (–)
\( \rho_c \) density of pure cellulosic material (kg m\(^{-3}\))
\( A_c \) pre-exponential factor for the oxidation of the cellulosic material (s\(^{-1}\))
\( E_c \) activation Energy for the oxidation of the cellulosic material (J mol\(^{-1}\))
\( R \) ideal gas constant (J K\(^{-1}\)mol\(^{-1}\))
\( Q_b \) exothermicity for the oxidation of biomass per kg of dry cellulose (J kg\(^{-1}\))
\( \rho_b \) density of bulk biomass within the compost pile (kg m\(^{-3}\))
\( A_1 \) pre-exponential factor for the oxidation of the biomass growth (s\(^{-1}\))
\( E_1 \) activation Energy for the biomass growth (J mol\(^{-1}\))
\( A_2 \) pre-exponential factor for the inhibition of biomass growth (–)
\( E_2 \) activation energy for the inhibition of biomass growth (J mol\(^{-1}\))
\( T_a \) ambient temperature (K)
\( T_g \) temperature of the ground (K)
\( q_r \) amount of heat generated (lost) in the bioreactor (kJ h\(^{-1}\))
\( q_w \) heat leaving the bioreactor as a result of the penetration phenomenon (kJ h\(^{-1}\))
\( q_k \) heat leaving the bioreactor as a result of the convection phenomenon (kJ h\(^{-1}\))
\( U \) penetration coefficient (W m\(^{-2}\)K)
\( A \) bioreactor surface (m\(^2\))
\( T_r \) medium temperature of the bioreactor (K)
\( T_0 \) external temperature (K)
\( V \) volume stream of air on the inlet to the bioreactor (m\(^3\)h\(^{-1}\))
\( \rho \) density of input air (kg m\(^{-3}\))
\( X \) absolute mass humidity of surrounding air
\( i_w \) absolute enthalpy of air on the outlet of the bioreactor (kJ kg\(^{-1}\))
\( i \) absolute enthalpy of the inlet air (KJ kg\(^{-1}\))
\( m \) mass of composting materials (kg)
\( c \) specific heat capacity of composting materials (kJ kg\(^{-1}\)°C\(^{-1}\))
\( m_R \) mass of composting reactor (kg)
\( c_R \) specific heat capacity of composting reactor (kJ kg\(^{-1}\)°C\(^{-1}\))
\( E_{bio} \) biological heat production (kJ d\(^{-1}\))
\( E_{con} \) convective heat loss (kJ d\(^{-1}\))
\( E_{wall} \) conductive heat loss form surface of reactor (kJ d\(^{-1}\))
\( E_{lat} \) latent heat of water evaporation (kJ d\(^{-1}\))

Acknowledgements
The authors would like to express their gratitude towards the financial support received from the Cultivation Plan for Youth Agricultural Science and Technology Innovative Talents of Liaoning Province (2014053), National 863 Project of China (2013AA102407), General project of the Education Department of Liaoning Province (L2014270) and the Project of Youth Fund in Shenyang Agricultural University (20121002).

REFERENCES


Marek, S., J. Magdalena and Z. Roman. 2003. In-vessel composting for utilizing of municipal