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# Literature Review on Composting Heat Recovery

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**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 microbial metabolic activity to release heat. High temperature could be got during the composting of garbage of urban life during a few days or even a few months (MSW; Hogland et al., 1996). Nearly 85% of industrial waste will be burned with temperature increases during the composting (Hogland et al., 1996). Substrate's biodegrade ability and energy content Determined the the composting process (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).

The traditional composting process generally includes four microbial stages: mesophilic, thermophilic, cooling and maturation, and compost is the last product (Haug, 1980). In order to obtain high quality compost with optimal maturity and stability, we must do everything possible to create favorable quality of the raw materials and efficient management of the compost process (Brinton et al., 1995; Butler et al., 2001; Gomez et al., 2006; Carballo et al., 2008).

In order to ensure the living environment of bacteria, the current composting mode is to maintain the temperature at 55°C. If there is no significant change in temperature control, the bacteria will survive well and the entire fever phase will become compact. In addition, compost materials mixed with kitchen waste, grass, and animal waste, these things are suitable for bacterial growth (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, a variety of crop straw, weeds, leaves, vines, peat, garbage, vegetable waste, kitchen waste and so on (Antizar et al., 2008).

2. Waste from Livestock and poultry industries. It is generally a substance that contains more nitrogen and bacteria that contain high-temperature fiber, such as human and animal urine, horse manure, sheep manure, old composting, ash and lime (Ahna et al., 2007; Tang et al., 2007).

3. Sewage sludge (SS), the structure and C/N of SS mixed with MSW could be improved, increase the nitrogen content of MSW for composting products, to achieve rapid disinfection purposes (Guardia et al., 2008; Chen et al., 1996; Banegas et al., 2007; Marek et al., 2003).

## 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). High temperatures (45-65°C) keeps several days to 6 weeks, it may be due to the loss of easily degradable organic matter, the deposit cooling or lack of moisture (below 50%) (Raclavska et al., 2011). For composting, the best moisture content is 50-70% (Richard et al., 2002; Vergnoux et al., 2009). Increasing the high temperature phase of the composting process can result in shortening the overall process time and decreasing the generation of noxious gases. The higher temperatures (70-80°C) clean compost, but agricultural waste does not require sanitation. So, the excess heat can be collected for else place (Bari and Koenig, 2001; Ekinci et al., 2006; Lin, 2008).

Table 1. Composting temperature

| Author | Year | Temperature phase | Best temperature (°C) | Advantages |
|---|---|---|---|---|
| Suler et al. | 1977 | thermophilic | 50-60 | |
| MacGregor et al. | 1981 | thermophilic | 52-60 | |
| Nakasaki et al. | 1985 | thermophilic | 50-60 | |
| Miller | 1992 | thermophilic | 55-65 | |
| Palmisano and Barlaz | 1996 | thermophilic | 55-59 | |
| Rao et al. | 1996 | Mesophilic | 37 | maximal mineralization of poplar wood carbon to $CO_2$ |
| Vikman et al. | 2002 | Mesophilic | 35 | maximum carbon converted into microbial biomass carbon |
| Liang et al. | 2003 | Mesophilic | 43 | greatest amount of cumulative $O_2$ uptake |

### *Heat production capacity*

Aerobic composting is in aerobic conditions, aerobic bacteria on the waste absorption, oxidation, decomposition. Microorganisms, through their own life activities, oxidize a portion of absorbed organic matter to simple inorganic matter while releasing the energy necessary for microbial growth activities (Sundberg, 2004). There is very limited data on the heat generated by the compost process, just as diverse as the compost's composition. Scarce researches has investigated the heat production capacity of compost as given is Table 2.

Table 2. The potential heat production of compost

| Author | Material | Year | Temperature phase | Heat production ($MJ\ kg^{-1}$) | |
|---|---|---|---|---|---|
| | | | | Average | Range |
| Guljajew and Szapiro | agricultural waste | 1962 | whole | 0.961 | 0.302-1.802 |
| Stainforth | wheat straw | 1979 | whole | 17.6 | |
| Sobel and Muck | wheat straw | 1983 | whole | 12.8 | |
| Steppa | MSW | 1988 | | | 9-11 |
| Ahn et al. | poultry manure and wood shavings mixture | 2007 | whole | | 16.83–19.7 |
| Klejment | MSW | 2008 | high temperature phases (>60°C) | 1.136 | |
| Irvine et al. | industrial sludge | 2010 | whole | | 7-10 |
| Bernstad and Cour | food waste | 2012 | lower heating value | | 1.7-6.3 |
| Lee et al. | livestock wastes | 2014 | whole | 18.82 | |

### *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 3. The values of compost thermal conductivity coefficient

| Author | Material | Year | Moisture content | Temperature (°C) | Density ($kgm^{-3}$) | Compost thermal conductivity coefficient |
|---|---|---|---|---|---|---|

| | | | (%) | | | ($Wm^{-1}K^{-1}$) |
|---|---|---|---|---|---|---|
| Ginkel | straw | 1996 | 75 | 50-60 | | 0.550- 0.670 |
| Kaleta | clover | 1999 | 40 | 20-80 | | 0.075-0.085 |
| Klejment | MSW | 2008 | 40 | 30-60 | 442-600 | 0.150-0.309 |

### *Theoretical modeling*

The composting model provides a systematic approach to dynamic warming and heat balance (Haug, 1993; Mason, 2006). Through the simulation results, it is possible to monitor the change between the different heat balance of groups throughout the composting process, rather than merely providing an indication of which heat balance group is more significant (Haug, 1993; Mason, 2006).

Nelson et al. (2003) analyzed a spatially uniform model according to the Semenovs theory used for thermal explosion, composting self-heating. The singularity function (G) is

$$G = \psi_b \exp[\theta] + (\psi_o \exp[\alpha_o \theta] - \theta)(1 + \beta \exp[\alpha_d \theta]) \tag{1}$$

Note that,

$$G_{\psi_b} = \exp[\theta] \neq 0 \tag{2}$$

The model investigates the cases when self-heating is related to purely biological heat-release and the combination of biology and chemistry heat-release. Since the system was described by a single (but not linear) and first-order ordinary differential equation, with few parameters (Schaeffer and Golubitsky, 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

$$(\rho C)_{eff} \frac{\partial T}{\partial t} = k_{eff} \nabla^2 T + Q_c (1-\varepsilon)\rho_c A_c \exp[\frac{-E_c}{RT}] + Q_b (1-\varepsilon)\rho_b \frac{A_1 \exp[\frac{-E_1}{RT}]}{1 + A_2 \exp[\frac{-E_2}{RT}]} \tag{3}$$

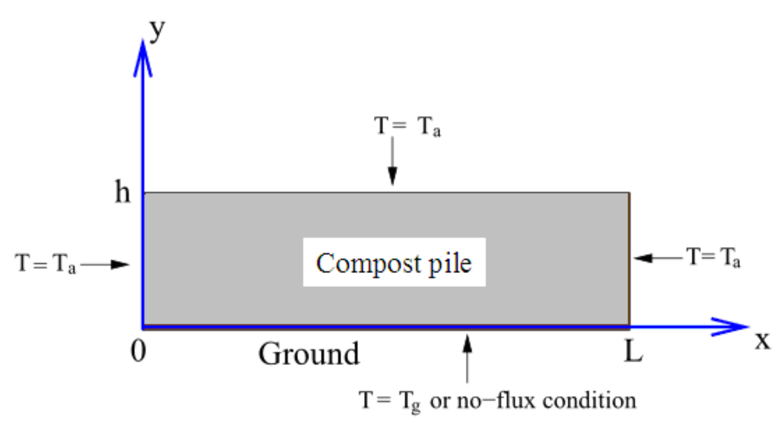


Figure 1. Schematic diagram showing the geometry of the two-dimensional compost pile with a rectangular cross-section and the corresponding boundary conditions (Sidhu et al., 2007).

Once the boundary conditions have been established, the expression of this model will be completed. The boundary conditions used in this study are specified in Figure 1, and are given explicitly below (Sidhu et al., 2007)

Boundary conditions:

$$T = T_a \quad \text{along} \quad x = 0, \quad x = L \quad \text{and} \quad y = h$$

$$T = T_g \quad \text{or} \quad \frac{\partial T}{\partial n} = 0 \quad \text{along the base} \quad y = 0, \tag{4}$$

Initial conditions:

$$T = T_a \tag{5}$$

The exothermic pattern of this model is affected with biological activity in the composting stack (Nelson et al., 2007). This feature illustrates the fact that microbes die or sleep at high temperatures. The exothermic mode caused by the oxidation reaction is modeled by the conventional way 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) analyzed heat of natural solid fertilizer composting process with neural network modeling. Research analyzed the neuro-predictive problem in the thermal process of compost and the emphasis is to place on estimating the heat loss caused by a portion of the exothermic reaction that taken place during this process (Boniecki et al., 2013). The equation is

$$q_r = q_w + q_k = 3.6UA\left(T_r - T_0\right) + \frac{V\rho}{X+1}\left(i_w - i\right) \tag{6}$$

Research results showed that neural modeling can be effectively used to estimate the heat that is emitted and lost during compost. Sensitivity analysis of the input variables through the model shows that several important parameters obtained in the process of heat loss assessment are $O_2$ (% oxygen), $CO_2$ (% of mass), TIME (process duration), T (bioreactor internal temperature), and V (flow rate) (Boniecki et al., 2013).

Wang et al. (2014) developed a heat balance model for composting to determine changes in heat loss components (convection, conduction, and latent heat losses) in the composting process. The thermal balance equation was

$$\left(mc + m_R c_R\right)\frac{dT}{dt} = E_{bio} - E_{con} - E_{wall} - E_{lat} \tag{7}$$

The results of this model indicate that during the entire process, the percentage of total heat loss convection, heat loss and latent heat loss varied greatly. The highest percentage of conduction heat losses are 38.9% and 57.7% of total heat losses with and without adiabatic modeling, respectively. Temperature changes and the entire heat balance process are affected by substrate decomposition (Wang et al., 2014).

## HEAT RECOVERY METHODS

Known limited studies on the heat recovery of composting have shown that it is a critical condition to strictly control the temperature in the bed. To prevent the temperature from falling below the temperature required for high-temperature composting, too much heat can’t be removed during composting (Chroni et al., 2009). On the other hand, losing a large amount moisture is not conducive to heat accumulation, but also slow down the composting process, so keep the entire composting process from over-ventilation. The current method of controlling the temperature of the composting process is usually to maintain the oxygen content of the reactor or to control the air content of the reactor by adjusting the temperature (Xiao et al., 2009). The following are two methods of composting heat recovery, respectively, direct and indirect methods.

**1. Direct recovery method**

A direct method is to extract heat from the material in the composting process.

Water heating

The first method is by circulating water pipes inside the heap or in the concrete slab. This method is more suitable for personal use. The process of piling up and disassembling requires installation and removal of pipelines, and the time and labor available to them for help. This is not the case for commercial use for the waste of time and labor (Smith and Aber, 2014). Another downside is the lack of mechanical agitation. But also easy to take away some of the heat in the cold water in the pipeline. The above situation is not conducive to the growth of microorganisms, and may also lead to corruption (Smith and Aber, 2014).

The method of extracting heat directly from manure is a simple and effective method pioneered by Pain et al. (2012). One of the heaps is to set water pipes in them, with pipes in 10 inches apart. When there is air through the heap will produce heat, water is taken away by the water pipes, as a radiation source for greenhouse (Pain et al., 2012).

Studies conducted by Lekic (2005) showed that the water temperature increases as it passes through the entire pipeline, theoretically 73% of the heat is absorbed by the water. The limitation of this study is the laying of pipes (Lekic, 2005). A solution proposed by Seki and Komori (1992) is to use packed column heating tower to concentrate the heat discharged into water.

Space heating

The second method in direct composting heat recovery is space heating, where heat is pushed out (forced aeration) or pulled through (negative aeration) a composting pile. Most commonly accomplished by placing the compost pile on a well-ventilated and level floor, pouring the perforated PVC pipes into the concrete, covering it with a perforated cover and finally covering it with 8-inch sawdust. By moving the whole body mechanically, air enters the heap, removing excess heat while generating heat (Rynk, 1992; Epstein, 2011; Smith and Aber, 2014). However, this method requires that there be a strong microbial population in the heap and that it is difficult to collect the collected heat with a mere 13.4% availability, thus it has some limitations (Themelis, 2005). The invention was originally derived from the New Alchemy Institute, they warmed a greenhouse with compost vapor by biofilter in the winter (Fulford, 1986). Although this study is mostly used for horticulture, it plays an important role in prolonging the season time and reducing greenhouse energy loss under cool climatic conditions.

**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 speaking, the moisture in the feedstock is evaporated by the biological response of a specific set of well-fed fermenting microorganisms that produces heat above 80°C and thus evaporates residual materials and food waste were compared,18.82 MJ/kg, in a heating value test. One of the advantages of ACES is that it does not require the removal of waste water compared with the traditional method, ACES is more like a method does not need to rule out any substance, but does not require additional energy. Microbials can consume organic matter in the raw material and emit heat, and can be the temperature reached 80°C-90°C. The use of heat generated, the raw water can be volatile out, which is the rest of the traditional methods can’t be achieved (Lee et al., 2014).

About how to handle the liquid in livestock excrement. How to deal with these liquids is the biggest problem converting raw materials into heat. Because raw materials are mixed with up to 90% moisture, the remaining solids have very high potential for energy production, such as

10.46-14.64 MJ $kg^{-1}$ (Lee et al., 2014), which requires reasonable treatment of the liquid. The usual approach is to evaporate. If electricity or natural gas is used for evaporation, the cost of the project will be increased. In addition, since the moisture inside the raw material itself is not easily dried, it takes a long time to evaporate, and the dried material also has unpleasant odor (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

| | |
|---|---|
| $\psi_b$ | Semenov number for the biomass |
| $\theta$ | non-dimensionalized bioreactor temperature, |
| $\psi_o$ | semenov number for the oxidation of cellulosic materials |
| $\alpha_o$ | 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 inhibibition 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 ($Wm^{-2}K$)
$A$ 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 ($m^3h^{-1}$)
$\rho$ density of input air ($kgm^{-3}$)
$X$ 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 ($kJ\ d^{-1}$)

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