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Review

Heat potential, generation, recovery and utilization from composting: A review

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ABSTRACT

Composting is an effective process for treating organic solid waste (OSW). There is a growing interest in recovering and reusing heat from composting, in the context of climate change and fossil fuel depletion. Several literature reviews have been conducted to address the composting process; however, several engineering aspects, including heat estimation, recovery, and utilization, are inadequately addressed in current reviews. To fill this knowledge gap, we bring together the current knowledge on the heat from composting and provide a discussion on the methods for calculating the heat potential of OSW, estimating the amount of heat production and recovering the generated heat. Moreover, we summarize the utilization of generated heat and point out the challenges and the outlook for future research. The results show that the heating value of different OSW can be calculated by ultimate analysis, proximate analysis, or composition analysis. Moreover, different methods have been used for heat production estimation: the degradation method can adequately describe the composting process, O_2 method is simpler to implement, and heat balance method is only valid at large scale reactors. Different types of reactors use different techniques for heat recovery: water jacket method is suitable for small-scale reactors, while tube buried-in pile method and percolation water method are especially suitable for lignocellulosic biomass composting. Heat exchanger in the head space method and low-temperature heat recovery technologies are mainly used for commercial reactors. The heat recovered from composting is potentially suitable for building applications such as hot water service, flooring heating and wall heating.

1. Introduction

In recent years, the amount of solid waste has increased rapidly with growing population, urbanization, and industrialization (Singh et al., 2014). It is reported that about 11 million tons of solid waste will be produced every day in the world by the end of the 21st century (Hoornweg et al., 2013). Organic solid waste (OSW) is the largest part of the solid waste, accounting for 46% of the total solid waste generation (Hoornweg and Bhada-Tata, 2012). There are several main components of OSW: sewage sludge, kitchen waste, lignocellulosic waste, and manure waste (Chen et al., 2020). The huge amount and the different components of OSW make the management a global challenge (Potdar et al., 2016).

Currently, the management of OSW includes landfilling, incineration, and biological treatment (composting and anaerobic digestion), which is shown in Fig. 1. The landfill competes with living space for human beings (Slater and Frederickson, 2001) and may pollute the soil and groundwater (Ančić et al., 2020; Mor et al., 2006; Yang et al., 2013). Incineration reduces the volume of OSW effectively; however, it may generate harmful emissions, like NO_x, CO, and fine particles (Wang et al., 2012). Moreover, the high moisture content of OSW prolongs the drying process, which is not optimal for incineration (Lin et al., 2015). On the opposite, biological treatment of OSW is an environmental-friendly management method demanding high moisture content for microbial growth. The biological treatment of OSW mainly includes anaerobic digestion and aerobic composting. Anaerobic digestion of OSW is carried out in the absence of O_2. In anaerobic digestion, microorganisms degrade OSW into gaseous products like CH_4 and CO_2 as well as solid compounds like digestate (Kumar and Samadder, 2020). While aerobic composting is under the presence of O_2 and yields compost as the final product (Istrate et al., 2020). Fig. 1 summarizes the current management methods of OSW.

Compared with other management methods of OSW, composting has many advantages. First of all, composting has lower technical

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complexity and capital investment (Cadena et al., 2009). Secondly, composting causes little environmental burdens as pathogens are usually killed during the high temperature phase (Rai et al., 2021). Moreover, the residue of composting is humus (soil improver) and can be applied to agricultural soils (Boldrin et al., 2009; Weber et al., 2014). OSW is amenable to composting as it consists of heterogeneous organic matter, including sugars, fats, proteins, hemicelluloses, celluloses, and lignin, which are important energy sources for involved microorganisms (Cheung et al., 2010). During composting process, microorganisms decompose OSW into CO_2, H_2O, NH_3 and release considerable amounts of thermal energy (Bell, 1970; Ghaly et al., 2006; Haug, 1993; Mudhoo and Mohee, 2008). This process is shown in Eq. (1):

$$Organic\ matter + O_2 \rightarrow CO_2 + H_2O + NH_3 + humus + energy \quad (1)$$

Part of the generated energy is used for sustaining microbial metabolism, and the rest is normally lost to the surrounding environment as heat (Tuomela et al., 2000; Zhao et al., 2017). However, the generated heat is usually ignored as the main aim of composting is the safe disposal of OSW and the production of soil improver (Boldrin et al., 2009; Bollen et al., 1989; Haug, 1993; Lu et al., 2001). With the rapid increase of worldwide energy demand, the generated heat gains increasing interest, as it can be seen as a sustainable alternative to fossil fuels and one of the primary possibilities for preventing global warming (Benjamin et al., 2020; Istrate et al., 2020; Wei et al., 2017).

Over the past decades, many research papers about the heat generated from composting have been published (Allain, 2007; Ge et al., 2020; Hess et al., 2004; Liang et al., 2003; Sokolovs et al., 2015; Themelis, 2005; Wu et al., 2020; Xu et al., 2020; Yu et al., 2020). There are only several review papers relating to heat (Ajmal et al., 2020; Mason, 2006; Smith et al., 2017; Walling et al., 2020; Zhao et al., 2017). These reviews have studied: 1) the mathematical models of composting process, including models of energy balance and mass balance or 2) different heat recovery data and different heat recovery technologies. For example, Istrate et al. (2020) compared and assessed the life-cycle environmental consequences of different waste-to-energy solutions on municipal solid waste (Istrate et al., 2020). Walling et al. (2020) discussed the models that used to describe the composting process; however, the heat generation during composting was not discussed in-depth. Ajmal et al. (2020) reviewed the mathematical models of in-vessel composting processes from energy balance perceptions and reported some models used for describing the degradation process, but the advantages and disadvantages of these methods were not discussed. Smith et al. (2017) summarized 45 composting heat recovery systems and reported their heat recovery data chronologically; nevertheless, how the data was calculated was missing. Zhao et al. (2017) reviewed the advances in heat recovery systems from composting; however, the comparison of these methods was not analyzed.

Different literature involves different methods to estimate, recover and reuse the generated heat. The combination and in-depth discussion of these methods are needed to understand, design and operate different composting systems as well as improve their heat performance. In this review paper, we firstly report the heat potential of different components of OSW. Thereafter, we introduce different methods for estimating the specific heat production during composting and discuss their advantages and disadvantages. Next, we summarize the different heat recovery systems that have been used for composting and evaluate both traditional heat recovery technologies and low-temperature heat recovery technologies. Finally, we summarize the current heat utilization cases and give an outlook for future study.

2. Heat potential of composting and its estimation

Generally, composting consists of four stages according to its temperature regimes: mesophilic stage, thermophilic stage, cooling stage, and maturation stage (Partanen et al., 2010). Fig. 2 displays the changes in the temperature and heat production rate during these four stages. In the mesophilic stage and thermophilic stage, the heat production rate is high and maintains high for a long period, because the involved microbes quickly degrade the energy-rich and easily degradable compounds (starches, sugar and fats), and some more resistant substances (proteins, hemicellulose and cellulose). Also, high temperature can help accelerate the breakdown of proteins, fats and complex carbohydrates like cellulose and hemicellulose. These two phases can last for several weeks (in food waste composting) to several months (in lignocellulosic waste composting) under proper insulation (Fan et al., 2021; Insam and De Bertoldi, 2007; Tuomela et al., 2000; Ye et al., 2019). In the cooling stage and maturation stage, the microbial activity declines due to the depletion of easily degradable materials. As a result, the heat production

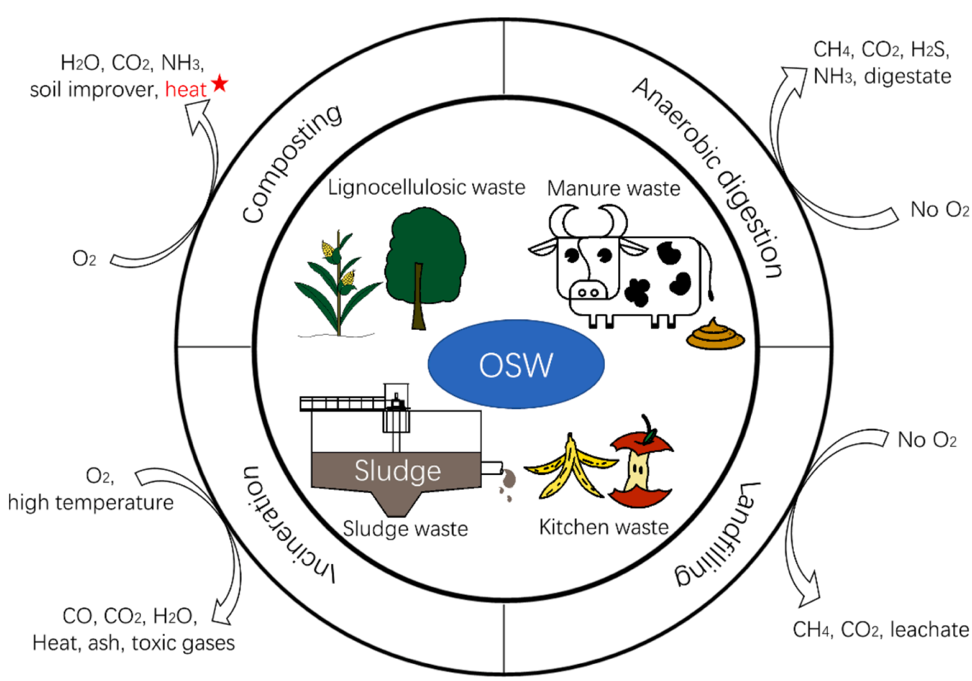

Fig. 1. Graphic outline of current organic solid waste management.

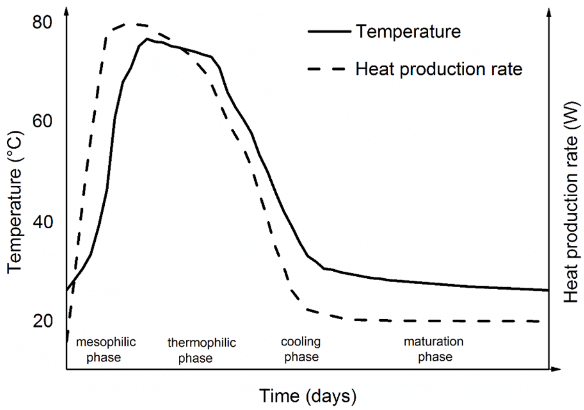

Fig. 2. Schematic figure of composting process (Xiao et al., 2011; Yeh et al., 2020).

rate decreases, and the temperature of the compost pile declines (Epstein, 2011; Luo et al., 2008). The cooling stage and maturation stage may last for several weeks to several months (Tuomela et al., 2000).

Composting process can release a large amount of heat, especially in the first two stages. The heat production in composting originates from the chemical energy stored in the organic matter (Haug, 1993). The ultimate energy from composting is the same as that from combustion of the substrates as both are aerobic processes if all substrates are fully oxidized (Smith et al., 2017; Sobel and Muck, 1983). Heating value (HV, in the unit of MJ/kg), namely calorific value, heat of combustion, or higher heating value, is defined as the "amount of energy released from combustion per kg of the mass". The HV is one of the most significant factors of OSW for carrying out energy analysis. The properties of different OSW components used in composting are shown in Table 1.

HV is conventionally obtained by complete combustion in calorimeters under controlled conditions (Demirbaş and Demirbaş, 2004). However, the calorimeter is sophisticated, time consuming and costly and requires the special set-up, measurement and calculation procedure (Nhuchhen and Abdul Salam, 2012; Sheng and Azevedo, 2005). Therefore, researchers have developed a series of empirical correlations from actual measurements to estimate the HV of OSW (Marlair et al., 1999). These empirical models are much easier and cheaper; therefore, they have been widely used. There are three types of empirical correlations for estimating the HV: ultimate analysis, proximately analysis and chemical composition analysis (Sheng and Azevedo, 2005). These methods have been successfully applied to lignocellulosic waste (Cordero et al., 2001; Demirbaş, 1997; Friedl et al., 2005; Huang and Lo, 2020; Jiménez and González, 1991), sludge waste (Abbas et al., 2011; Thipkhunthod et al., 2005), manure waste (Choi et al., 2014; Qian et al., 2018) and food waste (Johari et al., 2012; Nhuchhen and Abdul Salam, 2012; Sanli et al., 2014).

Table 1
The properties of four different organic solid waste components.

Substrates	Sources	Composition	Heating value (MJ/kg)	Reference
Lignocellulosic waste	Wood, wheat straw, corn straw, grass, bamboo	Cellulose, hemicellulose, lignin, ash	15–43	(Demirbaş and Demirbaş, 2004; Nhuchhen and Abdul Salam, 2012)
Food waste	Egg, meat, rice, oil, fruit and vegetables	Protein, lipid, fat, carbohydrate, inorganic compound	6–20	(Melikoglu et al., 2013; Menikpura and Basnayake, 2007)
Sludge waste	Domestic sludge, industrial sludge	Microorganism, organic fiber, extracellular polymer substance, inorganic particle	4–7	(Kim et al., 2005)
Manure waste	Chicken manure, horse manure, pig manure, cattle manure, human waste	Bedding materials, feces, urine	11–47	(Sahu et al., 2016)

Ultimate analysis, or element analysis, can give the elemental composition of different OSW. The principle of ultimate analysis is to calculate the quantity of oxygen or air needed to sustain the combustion process (Lyons et al., 1985). Thus, ultimate analysis determines the elements of OSW, usually include C, O, H, N, and S. Ultimate analysis has high accuracy; however, the process is slow and costly. The general equation of ultimate analysis estimating HV is described in Eq. (2).

$$HV = aC + bO + cH + dN + eS + f \tag{2}$$

where HV is the heating value of OSW (kJ), the a, b, c, d and e represent the calorimetric coefficients (in the unit of kJ) of carbon, oxygen, hydrogen, nitrogen and sulfur, respectively; C, O, H, N, S are the weight percent of the corresponding elements in OSW; f is a coefficient of ultimate analysis.

Proximate analysis gives the relative amounts of fixed carbon (FC), volatile matter (VM), ash content (ASH) of the OSW (Lyons et al., 1985). The amount of FC and VM mainly contributes to the HV of OSW. VM is the weight loss in mass of OSW by gradually but rapidly heating to 950 °C (Volborth, 1979). FC is the solid combustible residue that remains after the VM is expelled (Lomeda-De Mesa et al., 2020). ASH is the inorganic part of OSW, which cannot be oxidized during composting process (Uche Paul et al., 2017). The FC, VM and ASH represent the solid part, gaseous part, and non-combustible components, respectively (Callejón-Ferre et al., 2014). The general equation of proximate analysis estimating HV is described in Eq. (3):

$$HV = pFC + qVM + rASH + s \tag{3}$$

where FC, VM and ASH are the weight percent of the fixed carbon, volatile matter, and ash content in OSW; $p, q,$ and r represent their calorimetric coefficients (in the unit of kJ) respectively; s is a coefficient of proximate analysis. The proximate analysis is relatively simple and cheap compared to the ultimate analysis. Thus, the HV prediction using the proximate analysis results has been investigate by many researchers (Demirbas, 2008; Demirbaş, 2001; Nhuchhen and Abdul Salam, 2012; Sheng and Azevedo, 2005).

The last method to estimate the HV of OSW is chemical composition analysis, which is usually used for determining the HV of lignocellulosic biomass. Since the HV of cellulose, hemicellulose, lignin and extractives are consistent with their carbon content, the HV can be calculated by lignocellulosic composition (Callejón-Ferre et al., 2014; Demirbaş, 2001; Sheng and Azevedo, 2005), which is shown in Eq. (4).

$$HV = xCe + yHe + zLi + wE + u \tag{4}$$

where Ce, He, Li and E are the weight percent of the cellulose, hemicellulose, lignin, and extractives, respectively; $x, y, z,$ and w represent their calorimetric coefficients (in the unit of kJ) respectively; u is a coefficient of chemical composition analysis. On one hand, the chemical composition analysis has been mainly used for estimating HV of lignocellulosic biomass of which the hemicellulose, cellulose and lignin are the main components. On the other hand, the hemicellulose and lignin have

Table 2
Different methods used for estimating the heat potential of OSW.

Methods	Properties	Application
Calorimeters	Sophisticated, time consuming, costly, accurate, high accuracy	Lignocellulosic waste, food waste, sludge waste, manure waste
Ultimate analysis	Simple and cheap compared to calorimeter, high accuracy	Lignocellulosic waste, food waste, sludge waste, manure waste
Proximate analysis	Simple and cheap compared to ultimate analysis, low accuracy	Lignocellulosic waste, food waste, sludge waste, manure waste
Chemical composition analysis	Varies among different lignocellulosic species; easy, low accuracy	Lignocellulosic waste

different chemical structures and composition, leading the HV to vary among different lignocellulosic biomass species (Ozveren, 2017). Table 2 summarizes these methods for estimating the heat potential of OSW.

The specific models used for estimating the HV of different OSW components are summarized in Table 3. It can be seen in Table 3 that the coefficients of the equations are considerably different even in the same method, which means that the accuracy of each method must be critically evaluated to make a smaller deviation (Sheng and Azevedo, 2005). Generally speaking, the accuracy of the equations is determined by the number of samples used for estimation. With the development of scientific research and HV database, these three methods have been proved to have a strong ability in estimating the HV accurately, especially for the OSW with low heterogeneity (Ozveren, 2017).

Composting usually consists of various types of OSW components to ensure feasible composting conditions (Adamtey et al., 2009). For example, food waste is rich in nutrients while sludge waste has high moisture content. Lignocellulosic waste is often co-composted with food waste or sludge waste to obtain a proper C:N ratio and a proper porosity (Iqbal et al., 2010). The total HV of the mixed OSW can be calculated from the composition and proportion. In addition, calorimetric techniques can also be used for determining the HV of mixed substrates (Ahn et al., 2007; Prasityousil and Muenjina, 2013).

3. Actual heat production from composting and its estimation

OSW has great heat potential; however, decomposition of the organic matter is often not complete at the end of the composting process. The actual heat released from composting is lower than the potential heat available in the feeding substrates, and it is affected by the factors such as substrate mass, substrate degradability, and duration of composting (Smith et al., 2017; Sobel and Muck, 1983). The generated heat significantly affects the temperature, pathogen elimination, and the degradation rate of OSW. Moreover, the generated heat determines the types of heat recovery and heat utilization systems to be used. Thus, it is important to estimate and quantify the actual heat generation (Shaw and Stentiford, 1996).

There are several methods for quantifying the heat generation from composting, namely degradation method (DD), oxygen consumption method (OC), heat balance method (HB), CO_2 evolution method (CEM), temperature method (TEM), and heating value method (HVM). These methods are based on the fact that theoretical heat production in composting is positively correlated with O_2 consumption and degradation rate, which is also associated with the temperature and CO_2 production (Białobrzewski et al., 2015). Table 4 summarizes the different studies using these methods to estimate the actual generated heat from composting.

3.1. Degradation method

In composting, heat generation is accompanied with organic matter

Table 3
Models used for estimating heating value of different organic solid waste.

Models	R^2 or error band	Substrates	Reference
	Based on ultimate analysis		
$HV = 0.3137C + 0.0318O + 0.7009H - 1.3675$	0.834	Lignocellulosic waste	(Sheng and Azevedo, 2005)
$HV = 0.2949C + 0.8250H$	0.9737	Lignocellulosic waste	(Yin, 2011)
$HV = 0.00355C^2 - 0.232C - 2.23H + 0.0512C*H + 0.131N + 20.6$	0.943	Lignocellulosic waste	(Friedl et al., 2005)
$HV = 0.0053C^2 - 0.5321C - 2.8769H + 0.0608C*H - 0.2401N + 32.7934$	± 10%*	Lignocellulosic waste	(Nhuchhen and Afzal, 2017)
$HV = 0.301C + 0.525H + 0.064O - 0.736$	0.830	Lignocellulosic waste	(M. Ebeling and M. Jenkins, 1985)
$HV = 0.3443C + 1.192H - 0.113O - 0.024N + 0.093S$	0.9939	Lignocellulosic waste	(Huang and Lo, 2020)
$HV = 0.350C + 1.01H - 0.0826O$	0.935	Food waste, lignocellulosic waste	(Shi et al., 2016)
$HV = 0.2266C + 0.6544H + 0.1054O + 0.3927N - 1.6402S + 0.7357$	0.729	Manure waste	(Choi et al., 2014)
$HV = 0.4302C - 0.1867H - 0.1274N + 0.1786S + 0.1842O - 2.3799$	0.905	Sludge waste	(Thipkhunthod et al., 2005)
$HV = 0.4328C - 0.29773H + 0.28745N + 0.35608$	> 0.9	Lignocellulosic waste	(Huang et al., 2009)
	Based on proximate analysis		
$HV = 0.1905VM + 0.2521FC$	0.9714	Lignocellulosic waste	(Yin, 2011)
$HV = 0.1846VM + 0.3525FC$	± 10%*	Lignocellulosic waste	(Nhuchhen and Afzal, 2017)
$HV = -3.0368 + 0.2218 + 0.2601FC$	0.617	Lignocellulosic waste	(Sheng and Azevedo, 2005)
$HV = 35.43 - 0.1835VM - 354.3ASH$	NF	Lignocellulosic waste	(Cordero et al., 2001)
$HV = 0.3543FC + 0.1708VM$	NF	Lignocellulosic waste	(Cordero et al., 2001)
$HV = -10.81408 + 0.3133(VM + FC)$	< 10%*	Lignocellulosic waste	(Jiménez and González, 1991)
$HV = 0.1970VM + 0.3955$	0.806	Manure waste	(Choi et al., 2014)
$HV = 0.25575VM + 0.28388FC - 2.38638$	0.899	Sludge waste	(Thipkhunthod et al., 2005)
	Based on composition analysis		
$HV = 0.0889Li + 16.8218$	0.9504	Lignocellulosic waste	(Demirbaş, 2001)
$HV = 0.0877Li + 16.4915$	0.9302	Lignocellulosic waste	(Demirbaş, 2001)
$HV = 0.0979Li + 16.292$	NF	Lignocellulosic waste	(Acar and Ayanoglu, 2012)
$HV = \left(1 - \frac{ASH}{Ce + Li + E}\right)\left(0.17389\mathrm{Ce} + 0.26629\mathrm{Li} + 0.32187\mathrm{E}\right)$	NF	Lignocellulosic waste	(Jiménez and González, 1991)

Note: the amount of element (C,H,N,O,S), volatile matter (VM), fixed carbon (FC) are expressed in weight percentage; NF = not found; Ce, Li, He, E are weight percent of cellulose, lignin, hemicellulose and extractive on dry basis; * the value is the error band.

Table 4
The heat production estimated by different methods in different composting studies.

Substrate	Mass	Moisture content (%)	Method	Heat production (in rate or quantity)	Duration	Reference
Wood	50 t	60	DD	2.47 kWh/kg BOM	1 y	(Kimman, 2019)
Organic fraction of municipal waste	17.7–19.2 t	34–39	DD	0.75 kWh/kg BOM	50 d	(Robinzon et al., 2000)
Food waste, wood waste	419–697 g	55–65	DD and HB	0.74–1.19 kWh/kg VS	10 d	(Lemus and Lau, 2002)
Paper mill sludge, broiler litter	208 L	38–47	DD	0.22 kWh/kg DM/d*	NF	(Ekinci et al., 2006)
Biosolid, woodchips	208 L	38–47	DD	0.68 kWh/kg DM/d*	NF	(Ekinci et al., 2006)
Poultry manure, wood shavings	275 kg	62	DD	1.09–1.38 kWh/kg DM	30 d	(Ahn et al., 2007)
Food waste, maize straw	17.2 kg	71	DD	1.78 kWh/kg DM	56 h	(Xie et al., 2017)
Wood	6 g	250#	OC	0.24–0.52 kWh/kg DM	36 d	(Caizán Juanarena et al., 2016)
Wood	6.7 g	250#	OC	1.49 kWh/kg DM	42 d	(Fan et al., 2020a)
Wood	4.7 g	250#	OC	1.44 kWh/kg DM	95 d	(Fan et al., 2020b)
Food waste, wood chips	76 kg	63	OC	About 1.19 kWh/kg DM	37 d	(de Guardia et al., 2012)
Separated pig solid	145 kg	68	OC	About 1.50 kWh/kg DM	27 d	(de Guardia et al., 2012)
Pig manure, wheat straw	8 kg	50–67	OC	0.008 kWh/kg VS/h*	NF	(Ge et al., 2016)
Chicken manure, rice bran, sawdust	0.24 m^3	60	OC	0.56–2.22 kWh/m^3/h	About 340 h	(Seki and Komori, 1995)
Sludge, compost product	5 t/2d	52	OC	0.70 kWh/kg DM/d	NF	(Bach et al., 1987)
Sludge, compost product	5 t/2d	52	HB	0.70 kWh/kg DM/d	NF	(Bach et al., 1987)
Sludge, fat, poplar sawdust	32 kg	65	HB	1.19 kWh/kg DM	180 h	(Viel et al., 1987)
Tomato plant waste, wood shavings, municipal waste, urea	NF	60	HB	4.01 kWh/kg DM	114 h	(Ghaly et al., 2006)
Kitchen waste, garden waste	70 kg	NF	HB	0.39 kWh/kg WW	41 d	(Neugebauer, 2018)
Wheat straw, poultry manure, gypsum	5254–8583 kg	67–71	HB	0.34 kWh/kg WW	180 h	(Harper et al., 1992)
Manure, straw	45 kg	NF	HB	0.12 kWh/h*	NF	(Boniecki et al., 2013)
Tomato residues	50 kg	60–65	HB	0.53 kWh/kg WW	108 h	(Alkoaik et al., 2018)
Solid poultry manure, wheat straw, gypsum, water	1000 t	74	HB	0.37 kWh/kg WW	80 h	(Radojičić et al., 2017)
Chicken manure, hay, wood chips	120 L	60	HB	0.11 kWh/kg	44 h	(Nwanze and Clark, 2019)
Green waste, industrial sludge, liquid waste	NF	60	TEM	1.94–2.78 kWh/kg	15 d	(Irvine et al., 2010)
Solid fraction of pig slurry, lignocellulosic residues, plant, water	1725 g	65–70	TEM	1.75–5.08 kWh/kg TS	18 d	(Hunce et al., 2020)
Food waste, saw dust, mature compost	400 kg	65	TEM	0.83 kWh/kg WW	30 d	(Yeh et al., 2020)
NF	100 kg	43	HVM	0.50 kWh/kg WW	17 d	(Klejment and Rosiński, 2008)
Sawdust, grass, horse manure, potato paste, vegetables	15 m^3	65	HVM	0.26 kWh/kg	84 d	(Raclavska et al., 2011)

Note: NF = not found; DD = degradation method; OC = oxygen consumption method; HB = heat balance method; TEM = temperature method; HVM = heating value method; MC = moisture content; BOM = biodegradable organic matter; VS = volatile solid; TS = total solid; WW = wet weight; DM = dry mater; * the data is the peak value of heat production rate; # the data is the moisture content of the system.

degradation. Therefore, the degradation models describing the composting process can be used for estimating the actual heat production. Different degradation models have been proposed (Ekinci et al., 2006; Haug, 1993; Khater et al., 2014; Sobel and Muck, 1983; Talib et al., 2014), and the general form can be expressed as shown in Eq. (5):

$$Q_{bio} = HV_r \times r = HV_r \times \frac{dm}{dt} \tag{5}$$

Where Q_{bio} is the heat production rate of composting (W); HV_r is the heating value of the substrates (MJ/kg), defined as the amount of heat released per unit of substrate degradation; r is the coefficient of degradation rate (kg/s); t is the composting time (s); m is the weight of substrates (kg), which can be expressed as one of the follows: organic matter, dry matter, volatile solids, total solids, total organic carbon, carbon, wet weight, biodegradable volatile solids, or chemical oxygen demand (Higgins and Walker, 2001; Raclavska et al., 2011; Rada et al., 2014; Seki and Komori, 1984; Wang et al., 2014).

The degradation model can be regard as a function of HV_r and r. For simple and quick calculation, HV_r is regarded as a constant throughout the composting process (Raclavska et al., 2011), but in fact it gradually decreases. Ahn et al. (2007) proved that HV_r decreased with the increasing of composting time by using a calorimeter. To obtaina more accurate estimation, Wang et al. (2014) proposed an empirical model to describe the change of HV_r during composting process. For r, it is difficult to accurately measure the degradation rate especially in large scale reactors. Thus, many degradation models have been developed to describe the degradation process, such as first-order models and Monod-type models (Ajmal et al., 2020; Mason, 2006).

In the first-order models, r is related to the concentration of composting substrates (Haug, 1993). The first-order models are simple and easy because it only requires a single rate coefficient, which makes the first-order models the most prominent one (Walling et al., 2020). However, the first-order models cannot illustrate the effect of other factors, such as spatial distribution of substrates, decreasing availability of substrates, and concentration of microbial biomass, on the value of r. Hence, many derivatives have been proposed to give a more accurate description of the degradation process (Haug, 1993; Mason, 2006; Wu et al., 2011).

Another way is Monod-type model; it describes the relationship between the microbial growth and the degradation process in composting (Ajmal et al., 2020; Kaiser, 1996; Seki, 2000). Unlike the first-order models, Monod-type models require four or more coefficients, including maximum specific growth rate, decay coefficient, half-saturation coefficient and maintenance coefficient (Mason, 2006). It is challenging to obtain all those coefficients, because the microbial population growing on the composting substrates is variable. Besides, the degradation process may deviate from Monod-type when composting conditions, such as temperature, moisture, type of substrate and O_2 concentration, are limiting the microbial growth (Mohee et al., 1998; Wang et al., 2014). Moreover, the inhibitors also disrupt the accuracy of

Monod-type models (Bertolazzi, 2005; Gonzo et al., 2018; Sivakumar et al., 1994). These challenges limit the broader use of Monod-type models (Mason, 2006).

3.2. O_2 consumption method

O_2 is particularly important because it is needed in all aerobic degradations during composting. The principle of O_2 consumption method (OC) is that it calculates heat from the materials degradation. The biological reactions that take place in composting are often limited by the O_2 transfer rate (Paletski and Young, 1995). Besides, O_2 consumption has been proved as a useful indicator for the composting stability, microbial activity (Lasaridi and Stentiford, 1998; Lasaridi et al., 2000; Paletski and Young, 1995), degradation rate, microbial growth, and temperature change (Higgins and Walker, 2001; Tremier et al., 2005; VanderGheynst et al., 1997), which is important in composting studies.

O_2 profiles are widely used for predicting the heat production during composting, which has been validated extensively. Cooney et al. (1969) found that the heat production rate during metabolism was linearly correlated with the O_2 consumption rate by using a dynamic calorimetric technique. Harper et al. (1992) and Weppen (2001) also reported similar results. Fan et al. (2020a) demonstrated that O_2 was linearly related to the wood weight loss during wood composting, which is further linked to degradation rate. The heat generation during composting can be estimated and expressed based on O_2 dynamic using Eq. (6) (Bach et al., 1987; Haug, 1993; Nakasaki et al., 1987):

$$Q_{bio} = OCR \times HV_o = HV_o \times \frac{dO_2}{dt} \quad (6)$$

where HV_o is the heating value defined as the amount of heat generated metabolically per mole of O_2 consumption (kJ/mol O_2), OCR is the O_2 consumption rate (mol/kg), defined as the O_2 consumed per unit of time (mol O_2/s). HV_o is generally identified as a constant during one composting process (Caizán Juanarena et al., 2016; de Guardia et al., 2012; Haug, 1993). H_o is usually between 304 and 448 kJ/mol O_2 consumed (Mason, 2006), and it can be determined on the basis of chemical composition of the organic matter. In most cases, the O_2 consumption rate is determined by measuring the O_2 concentration difference in the inlet and outlet gas (Cooney et al., 1969). Besides, the O_2 consumption rate can be estimated by first-order models and Monod-type models (Mason, 2006; Yamada and Kawase, 2006).

Many researchers have improved OC for better heat estimation. For example, the effect of temperature and moisture content in the composting air were involved in O_2 models (Seki and Komori, 1995). de Guardia et al. (2012) calculated the heat generation via OC and found that the heat coefficient could significantly affect the temperature in the composting pile. In addition, the O_2 model was more accurate when taking the peak temperature of the composting pile into account (Ge et al., 2016).

3.3. Heat balance method

The heat balance method (HB), from the physical engineering point of view, has also been widely used under the condition that measuring or estimating the heat transfer in the composting environment is possible and valid. During the composting process, energy released from decomposition mainly results in the temperature increase of the organic matter and water, heat loss via convection and conduction, and water evaporation (Di Maria et al., 2008; Ghaly et al., 2006; Mason and Milke, 2005b). The heat essentially presents in two forms: sensible heat (energy associated with an increase in temperature) and latent heat (energy associated with phase transformation). The actual heat production can be calculated by measuring these components, as expressed in Eq. (7) (Bach et al., 1987; Ghaly et al., 2006; Haug, 1993; Wang et al., 2014):

$$Q_{bio} = Q_{sensible} + Q_{latent} = Q_{gas} + Q_{sub} + Q_{loss} + Q_{vap} + Q_{rad} \quad (7)$$

Where $Q_{sensible}$ is the amount of sensible heat (W), Q_{latent} is the amount of latent heat (W). To be more specific, heat balance components in composting model include heat production, convective heat loss of inlet and outlet streams (air, vapor, and water) Q_{gas} (W), sensible heat of composting materials Q_{sub} (W), conductive/convective losses through surface of reactor Q_{loss} (W), latent heat loss of water evaporation Q_{vap} (W), the radiant loss Q_{rad} (W) (Mason, 2006). Table 5 summarizes the models used to calculate the components of heat balance.

The equations of HB vary with different composting systems. Generally, Q_{vap} takes up the largest part of the generated heat, especially in large scale reactors (Bach et al., 1987; Di Maria et al., 2008; Robinzon et al., 2000; Themelis and Kim, 2002; Wang et al., 2014). Q_{loss} from the surface of reactor usually accounts more in small scale reactors than in big reactors (Ahn et al., 2007; Bach et al., 1987; Mason and Milke, 2005a). Q_{rad} is low and can be ignored compared to the total heat production in composting reactors (Ahn et al., 2007; Robinzon et al., 2000; van Lier et al., 1994). For example, Shaw and Stentiford (1996) reported that of the total heat loss from a pile, 88% was due to vaporization, 10% to dry air convection and 2% to conduction, with radiant heat transfer being assumed negligible. Q_{rad} is relatively large in open-air composting studies (Kimman, 2019; Robinzon et al., 2000). The heat balance method displays the distribution of generated heat from composting, helping define which heat recovery method is suitable for different reactors.

Many studies have validated the HB. Lemus and Lau (2002) compared the heat production calculated by HB and by DD, they pointed out that both methods were suitable for heat calculation. Bath et al. compared the heat generated calculated by OC and by HB and reported that the difference between the two methods was less than 0.5% (Bach et al., 1987). Xie et al. (2017) also reported the difference between OC and HB was less than 2%.

Table 5
The models estimating different components of heat balance.

Component	Nomenclature	Reference
$Q_{gas} = q_a(e_{out} - e_{in})$	q_a is the airflow (kg/s); e_{out} is the enthalpy of the exit air (kJ/kg); e_{out} is the enthalpy of the in air (kJ/kg)	(Wang et al., 2014)
$Q_{sub} = m[(1 - MC)C_s + C_wMC]\frac{dT}{dt}$	m is the mass of composting pile (kg); MC is the moisture content (%); C_s is the specific heat capacity of solid (kJ/K/kg); C_w is the specific heat capacity of water (kJ/K/kg); T is the temperature of composting pile (K); t is the time (s)	(Zhou et al., 2014)
$Q_{loss} = UA(T_r - T_a)$	U is the surface aera of reactor wall (m^2); U is overall coefficient of heat transmittance (kJ/m^2/K/s); T_r is the reactor temperature (K); T_a is the ambient temperature (K).	(Mason, 2006)
$Q_{vap} = q_aQ_v(h_{out} - h_{in})$	q_a is the flow rate of air (kg/s); Q_v is the enthalpy change of water vaporization (kJ/kg); h_{out} is the absolute humidity of exit air (kg/kg), h_{in} is the absolute humidity of in air (kg/kg)	(Wang et al., 2014)
$Q_{rad} = \sigma A(T_c^4 - T_h^4)F_aF_e$	σ is the Stefan–Boltzmann constant, 5.67 * 10^{-11} kJ/(s m^2 K^4); T_c is the temperature of the compost top surface (K); T_h is the temperature of the headspace between compost top surface and reactor lid (K); F_a is a configuration factor accounting for the relative position and geometry of the objects (dimensionless); F_e is the emissivity factor accounting for non-black body radiation.	(Ahn et al., 2007)

3.4. CO_2 evolution method, temperature method, and heating value method

Research efforts have also been made to correlate heat production with other variables, such as CO_2 evolution (Vlyssides et al., 2009), temperature of the substrates (Hunce et al., 2020; Lemus and Lau, 2002; Seki and Shijuku, 2012; Yeh et al., 2020), and heating value of the substrates (Ahn et al., 2007; Klejment and Rosiński, 2008)..

The first method is CO_2 evolution method (CEM). During composting process, the microorganisms degrade OSW and generate CO_2 (Wang et al., 2019). Changes of CO_2 concentration can express the degradation process. The CO_2 concentration can be measured by CO_2 meters or estimated by respiratory quotient (Kaiser, 1996; Sundberg and Jönsson, 2008). Sundberg and Jönsson (2008) validated that CO_2 emission could be used as an indicator to heat production during composting. Together with heat production, CO_2 emission could indicate the microbial activity during the continuously aerated composting (Sundberg and Jönsson, 2008). The general equation of CO_2 evolution method is shown in Eq. (8):

$$Q_{bio} = HV_c \times CER \quad (8)$$

where HV_c is the heat released per unit of CO_2 evolution (kJ/mol); CER is the CO_2 evolution rate (mol/s).

The second method, based on the temperature change, is temperature method (TEM). The temperature change of composting is the result of heat production and heat loss. Temperature is important because it indicates the microbial activity, composting stability, and composting maturation (Kumar et al., 2010). However, temperature, by itself, cannot indicate the amount of heat generation (Finstein et al., 1986). TEM is only valid when the heat loss data is zero or known. In the TEM, the generated heat is considered to be conserved both in the solids (composting substrates) and liquids (water) (Sundberg, 2005). Moreover, the specific heat capacity of the mixed solids and liquids should be known. For quick estimation, the specific heat capacity is assumed as a constant, and the composting process is assumed at constant pressure (Haug, 1993; Irvine et al., 2010). Under these conditions, the heat production rate can be obtained by observing the rate of temperature change during composting process (Hunce et al., 2020; Roland Mote and Griffis, 1982; Yeh et al., 2020). Another principle of TEM is to use a water bath to recover the generated heat and measure the temperature difference between the composting and water bath (Carlyle and Norman, 1941; Walker and Harrison, 1960). Due to these rigorous requirements, TEM is usually used in laboratory bench-scale composting units, which is usually shown in Eq. (9):

$$Q_{bio} = m_{mix} \times C_{mix} \times \Delta T = m_{water} \times C_{water} \times \Delta T \quad (9)$$

where ΔT is the temperature change of the substrates or water (K); C_{mix} is the specific heat capacity of substrates (kJ/kg/K); m_{mix} is the mass weight of OSW (kg); m_{water} is the mass weight of water (kg); C_{water} is the specific heat capacity of water (= 4.2 kJ/kg/K).

Another method is heating value method (HVM). The principle of HVM is that the HV of the composting substrates decrease gradually due to the microbial degradation during composting process (Ahn et al., 2007; Wang et al., 2014). The difference between the HV of composting substrates at the beginning and at the end of the composting indicates the amount of energy released from degradation (Klejment and Rosiński, 2008). Usually, a calorimeter is needed to accurately determine the HV of the mixed composting substrates (Raclavska et al., 2011). The general equation of TEM method is shown in Eq. (10):

$$Q_{bio} = HV_{ini} - HV_{fin} \quad (10)$$

where HV_{ini} is the HV of substrates at composting beginning (kJ/kg); HV_{fin} is the HV of substrate at the composting end (kJ/kg).

3.5. Comparison between different methods

In this review, we introduce different methods estimating the specific heat production from composting. Among all these methods, DD, OC, and HB are widely used. DD have been developed in both commercial reactors and lab-scale reactors, which is because that DD can also be used for studying how the operational parameters, such as moisture and aeration rate, affect the heat production. However, it is difficult to propose deterministic models describing all the composting processes under different operational parameters (substrates, aeration, temperature and moisture content) and different geometric configurations (size and shape of the reactors) (Seki, 2000). If all those factors are taken into consideration, DD models are usually complex. Moreover, the validation of DD models might be difficult and time-consuming.

OC is a feasible approach to calculate the actual heat production during composting. Firstly, the expression of OC is simple and easy to reproduce. The heat can be calculated without understanding the degradation process. Secondly, the O_2 consumption rate can be continuously measured, not only in commercial reactors (de Guardia et al., 2012; Gómez et al., 2006), but also in lab-scale studies (Fan et al., 2020b). Thirdly, the validation process of OC is simple: the only required parameter is HV_o. The disadvantage of OC is that it might require specific instrumentation and skilled labor (Gómez et al., 2006).

HB is critical to the energy analysis, which is widely used for the composting of mixed substrates, especially at pilot and commercial reactors where the data of latent heat and heat loss is significant. HB can give some hints to improve the available heat of composting reactors by reducing other heat loss components. Moreover, HB works well in continuously running reactors, which can be used to calculate the heat production (rate) without understanding the composting process. Different from DD and OC, HB considers all heat losses and transfers around the composting reactors and piles. External heat inputs, such as solar energy and heat generated from operating machines, might interfere the results. Thus, the disadvantage of HB is that it is usually difficult to measure all the required components of heat balance.

Other methods like CEM, TEM and HVM have been limitedly studied. For CEM, few researchers linked CEM to heat production. This might attribute to the low accuracy of CEM. CO_2 dissolves in water (40 mg/L water at 25 °C and 1 bar), and the solubility of CO_2 depends on pH and temperature (Wiebe and Gaddy, 1940). Therefore, CEM is less accurate

Table 6
Different methods used for estimating the actual heat generation during composting.

Methods	Properties	Application
DD	Suitable for mechanism study and process study; dependent on the degradation process, inhibitors and experimental conditions; complex validation and derivatives required	Large and small reactors
OC	Independent of the degradation process; based on the principle of materials degradation; easy and simple; continuous measurement; specific equipment and labor required	Large and small reactors
HB	Independent of the composting process; suitable for heat distribution study; difficult to measure all the components	Large reactors
CEM	Independent of the composting process; easy and simple; based on the principle of materials degradation; continuous measurement; heavily dependent on the CO_2 solubility and pH	Large and small reactors
TEM	Easy and simple; only valid when the heat loss is zero or known and the specific heat capacity of OSW is constant	Pilot reactors
HVM	Handy and easy; low sample representativity; not able to describe the composting process	Large reactors

Note: DD = degradation method; OC = oxygen consumption method; HB = heat balance method; CEM = CO_2 evolution method; TEM = temperature method; HVM = heating value method.

than OC. TEM works in the principle of HB, however, it is only valid when the heat loss data is zero or known. TEM cannot be used for commercial composting reactors because TEM fails to measure the latent heat, which takes a large part of total heat. HVM is handy and easy. However, the accuracy of HVM is highly dependent on the representativity of samples (although multi-sampling can reduce the deviation error), which limits its application remarkably, especially in large reactors with low homogeneity. Table 6 summarizes the properties of these methods that reviewed in this study.

4. Heat recovery from composting

Heat accumulation in composting could hinder the composting process. If all the heat generated during the decomposition remains in the compost, the temperature of composting will rapidly rise to thermophilic conditions and reach a temperature where most microbial activity stops (> 70 °C) (Cooney et al., 1969). Another problem is that the generated heat might dry out the composting pile (Finstein et al., 1992). As a consequence, the energy generation rate will decline quickly until the temperature drops in a proper range (generally between 40 and 60 °C). Thus, the excess heat must be removed to keep the compost at a proper temperature range in order to achieve high biological activity and maximal heat generation (Mudhoo and Mohee, 2007; Shaw and Stentiford, 1996). The removal of excess heat from compost pile can be recovered via several methods. These heat recovery methods vary depending on the composting substrate, composting method, temperature, composting scale, heat exchanger and even to geographical information (Smith et al., 2017; Yeh et al., 2020). There are generally two types of heat recovery technologies applied to composting, namely traditional heat recovery technologies and low-temperature heat recovery technologies. Traditional heat recovery technologies work in the principle that heat naturally flows from higher temperature to lower temperature. The traditional heat recovery technologies include water jacket method, tube buried in the pile (TBP), heat exchanger in the headspace of composting (HEH), and percolation water (PW). Low-temperature technologies use special working fluid with low boiling point to recover heat. Low-temperature heat recovery technologies that have been applied to composting include heat pump, organic Rankine Cycle (ORC), thermo electric generators (TEGs). Fig. 3 summarizes and describes the schematic drawing of these methods.

In Fig. 3, the composting pile in the reactor produces heat. The first recovery method is water jacket method (shown in Fig. 3(a)), consisting of water tube coated on the surface of the reactor/pile. The heat generated in the reactor heats the water via conduction (Viel et al., 1987). The second method is TBP method, which is shown in the part (b) of Fig. 3. In this system, heat is recovered by recirculating the water through a plastic/metal tube buried in the composting pile. Generally, the inlet cold water goes through the tube and carries the heat mainly via conduction (Pain, 1972). The third is HEH method (part (c) of Fig. 3) accomplished by placing a heat exchanger in the reactor headspace or in the exhaust air. By mechanical aeration, fresh cool working fluid is pumped in, meanwhile the excess heat is removed by pumping out the heated fluid (Zhao et al., 2017). The heat in the fluid can be efficiently recovered by heat exchangers (Radojičić et al., 2017). The part (d) of Fig. 3 demonstrates the PW. In PW, water is usually sprayed, percolated, collected and recirculated. The percolated water is heated via conduction during the percolated process, and the heat is removed in the collection process by using a heat exchanger. The last type of methods is the low-temperature heat recovery technologies, which can efficiently recover heat from a low-temperature heat source (< 100 °C). Some of these technologies, such as heat pump, organic Rankine cycle (ORC), and thermo electric generators (TEGs), have been successfully applied to composting (Varga and Palotai, 2017). The ORC and heat pump are shown in the part (e) of Fig. 3. Table 7 summarizes the different heat recovery methods from different composting studies.

4.1. Water jacket method

Water jacket is commonly used for controlling temperature of reactors. It can also be used for recovering heat from exothermic reaction reactor via conduction. This method is effective in pilot and lab-scale reactors because only in those reactors, the conducted heat loss through reactor sidewalls is considerable (Ghaly et al., 2006). Moreover, the water jacket method is not suitable for commercial reactors because of their huge surface area. The water jacket method does not influence the composting process, however, its accuracy is low due to the substantial heat loss. To reduce the heat loss, Viel et al. (1987) used a double layer water jacket to recover the generated heat from composting and achieved an average heat recovery rate of 4 W/kg DM for 56 h.

4.2. Tube buried in the pile method

Another recovery method is tube buried in the pile method (TBP). It is a throwaway method which is optimal to long retention time composting. TBP method has low cost and maintaining cost because it is often ventilated naturally (Pain, 1972), which also means a huge heat loss. It has been reported that about half of the generated heat could be lost to the environment by using TBP method (Kimman, 2019). In order

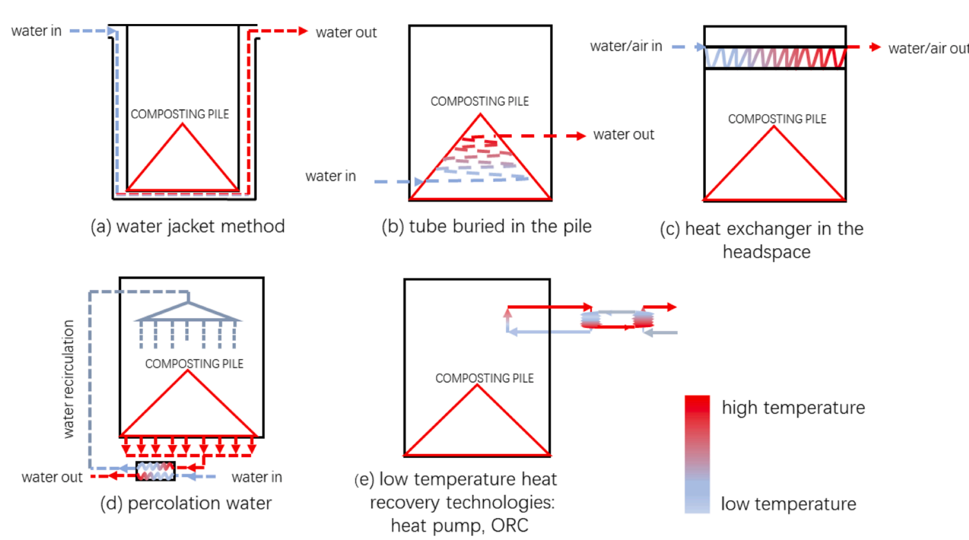

Fig. 3. The graphic illustration of different heat recovery methods.

Table 7
Different heat recovery studies reviewed in this paper.

Composting substrates	Mass	Moisture (%)	Methods	Heat recovery (in rate or quantity)	Duration	Reference
Sludge, fat, poplar sawdust	32 kg	65	Water-jacket	0.22 kWh/kg DM	56 h	(Viel et al., 1987)
Wood	50 t	60	TBP	1.18 kWh/kg BOM	1 y	(Kimman, 2019)
Woodchips, horse manure, vegetable waste and leaves	5803 kg	47.5	TBP	0.45–0.62 W/kg DM	3 d	(Bajko et al., 2018)
Chicken manure, hay, wood chips, water	120 L	60	TBP	About 200 W*	NF	(Nwanze and Clark, 2019)
Chicken manure, rice bran, saw dust	0.24 m^3	60	TBP and HEH	0.01–0.03 kWh/m^3 WW	7–14 d	(Seki and Komori, 1995)
Green waste, industrial sludge, liquid waste	NF	60	HEH	1.94–2.78 kWh/kg WW	15 d	(Irvine et al., 2010)
Food waste, green waste	189 t	62	HEH	0.30 kWh/kg DM	21 d	(Rada et al., 2014)
NF	100,000 t	NF	HEH	2.12 W/kg WW	NF	(Anderson et al., 2016)
Woodchips, horse manure, fresh grass, leaves, matured compost	6984 kg	58	HEH	0.14 kWh/kg DM	36 d	(Bajko et al., 2019)
Cow manure, horse manure/bedding mix, waste hay	136 t	60	HEH	0.13–0.24 kWh/kg DM	60 d	(Smith and Aber, 2018)
Manure, bedding and refusal feed	40 t	NF	HEH	0.22–0.29 W/kg WW	NF	(Brown, 2015)
Yard waste	About 0.5 m^3	15[a]	HP	About 1 kW/m^3	5 d	(Jaccard et al., 1993)
Food waste, yard waste, mixed paper	96 t	65	HP	1.11–1.38 kWh/kg OM	20 d	(Di Maria et al., 2008)
Organic fraction of MSW	32,000 t	NF	ORC	0.61 W/t WW	1 y	(Micalea, 2014)
Fruit waste, meat waste, paper and yard waste	20,000 t	63	ORC	0.05–1.25 W/t WW	1 y	(Di Maria et al., 2014a)
Municipal waste	20,000 t	63	ORC	0.45–0.6 W/t WW	1 y	(Di Maria et al., 2014b)
Garden waste, food waste	450–650 m^3	NF	TEGs	175 mW/m^{2}*·[b]	NF	(Rodrigues et al., 2018)
Chicken manure, rice hulls, sewage sludge	0.24 m^3	67	TEGs	7 W*	NF	(Shangguan et al., 2020)

Note: NF = not found; TBP = tube buried in the pile; HEH = heat exchanger in the headspace; WIP = with-in tube; HP = heat pump; ORC = organic Rankine Cycle; TEGs = thermoelectric generators; BOM = biodegradable organic matter; WW = wet weight; DM = dry mater; * the data is the peak value of heat production rate;.
[a]the initial moisture was low (15%), but water atomizers were used to humidify the composting material.
[b]the data was the maximum power density, m^2 was the dimension of the TEGs system.

to reduce the heat loss, the composting heap should be in the shape of the truncated cone, covering with a layer of straw or leaves (Roman, 2015). Moreover, the recovery efficiency of TBP, defined as recovered heat over total generated heat, is low as it collects little latent heat in the air. The conductivity of the substrates also affects the recovery efficiency of TBP. TBP is not suitable for commercial reactors, as it is labor/time intensive (Smith et al., 2017). TBP is often used in lignocellulosic waste composting aiming to provide heat for household use (Smith, 2016).

TBP method was pioneered by Pain in the 1970′s (Pain, 1972) and is still in use today. Seki and Komori (1993) reported that only 0.3% of the whole amount of energy generated in the composting was recovered by TBP method; most of the energy was lost to the surroundings via convection and conduction (Seki and Komori, 1993). In Lekic's study, about 73% of the theoretical value of heat energy was recovered by using polyethylene pipes buried in the composting piles, and the high efficiency was due to the low heat loss (Lekic, 2005). Besides, a low-density polyethylene tube was proved to be well designed for a composting of wood chips, horse manure, leaves and vegetable waste, and the whole system worked good without any significant problems in heat transferring (Bajko et al., 2018). Seki et al. (2014) used a flexible stainless tube to extract heat from a bamboo composting pile; the outlet temperature of water could reach 50–65 °C after 90 h, and it was possible to extract and utilize the generated heat for up to 1000 h. Nwanze and Clark (2019) found that the temperature was sensitive to the water flow rate of a copper tube during thermophilic stage, and more heat could be extracted with higher water flow rates (1147 ml/min).

4.3. Heat exchanger in the headspace

Another heat recovery method is heat exchanger in the headspace (HEH) method. HEH has high efficiency because it can collect the latent heat in water vapor and the sensible heat in air, which account for a large proportion of the total heat generation. The recovery efficiency can be even higher with multiple circulation times of the heat exchanger. HEH has little influence on the composting pile. Thus, HEH has low maintenance cost and long life span with multiple composting processes (Smith et al., 2017). This approach is mostly used in commercial reactors as it combines heat recovery with aeration, saving a lot of energy and cost. The main disadvantage of HEH method is that HEH would lead to condensation of water vapor, and the air recycling could dry out the composting heap.

It was reported that a HEH combined a flexible pipe set along the side wall could recover 16–22% of the total generated heat (Seki and Komori, 1995). Irvine et al. (2010) used HEH to collect heat from composting. In their report, the temperature of the outlet water was 47 °C and could even increase to 60 °C when the heated water passing through the multiple tunnels in series of the heat exchangers; they also compared the cost of operating a composting, solar thermal and ground source heat pump system, and found that composting with HEH was the most reliable one. Besides, the composting could be combined with solar updraft tower for heat production, it was reported that composting could supply 34% of the total energy gain with HEH (Anderson et al., 2016). Smith and Aber (2018) found that the generated heat recovered by HEH for a food waste composting plant could be supplied to a heat sink. The vapor temperature higher than 50 °C was sufficient for heat recovery (Smith and Aber, 2018). Bajko et al. (2019) built and tested the HEH as a part of pilot-scale composting heat recovery system, and they suggested that HEH could also be extended to larger scales composting operations.

4.4. Percolation water method

Another possible heat recovery method is percolation water (PW) method. In PW, water is sprayed to the composting pile, and the water percolates through the composting substrate via gravity. During this process, the percolated water, or leachate, is heated by the composting pile via conduction. The amount of heat transferred depends on the retention time. The water is usually collected from the bottom of the composting pile and flowed to a buffer tank for further heat recovery, which is often done by a heat exchanger. After that, the cooled water is pumped from the buffer tank to the top of the composting pile and sprayed again for next circulation. The PW method is only possible if the composting substrate has big particle size and high porosity, like wood chips. This method was tested in Leeuwarden, the Netherlands in an insulated 80 m^3 tank (Scholtens, 2018). In this case, the percolated water could reach temperatures between 40 and 50 °C (unpublished results).

The percolated water is usually considered as a source of nutrients or inoculum (Joanna et al., 2005; Ming et al., 2008; Roy et al., 2018). One advantage of PW is that it can conserve the microorganisms and nutrition, which is important in nutrients-poor composting systems (Ming et al., 2008). Another advantage is that PW can enhance the circulation of nutrition and microbial activity (Zheng et al., 2020), which is optimal for a homogenized composting. The disadvantage of PW is that it is hard to control the retention time of the percolation process, and the humidity of the composting pile and final compost product.

4.5. Low-temperature heat recovery technologies

Heat generated from composting is a low-temperature energy source because its temperature ranges between 20–80 °C (Xia et al., 2019). Traditional heat recovery technologies might have low energy efficiency dealing with the low-temperature heat sources (Ling-Chin et al., 2018; Yang et al., 2019). To improve the energy efficiency, low-temperature heat recovery technologies have been advanced continuously and some of them have been used for composting.

Heat pump (HP) is one of the low-temperature heat recovery technologies commonly used for space cooling and heating. HP can convert low-temperature heat to high-temperature heat by an electrical pump. It can efficiently transfer heat from the exhaust air of the composting to the water that needs to be heated (Willem et al., 2017). The coefficient of performance (COP) of HP is strongly dependent on the temperature of the composting. Once the COP has been determined, the heat recovery rate can be estimated. It was reported that a HP could recover 1 kW/m^3 energy from a continuous yard waste composting in the thermophilic stage (Jaccard et al., 1993). Keil et al. (2008) reported a HP could provide a hot water with a constant temperature at 82 °C by recovering heat from a municipal waste composting plant in Germany, with a COP of 1.6 (Keil et al., 2008). The potential of using HP to recover heat from composting for civil use was evaluated by Di Maria ; result shows that the HP increased both the temperature and amount of heat released by composting (at 55–65 °C), achieving about 4000-5000 kJ/kg OM heat at 80–90 °C with a COP ranging between 3.5 and 6 (Di Maria et al., 2008).

Organic Rankine cycle (ORC) is a promising technology to recover heat from composting due to its simplicity, high reliability and economic advantages (Yari et al., 2015). ORC uses organic working fluids with low boiling points to recover low-temperature heat, and generates electricity by using an evaporator and a turbine (Chen et al., 2010). ORC has low maintenance and personnel costs; however, the energy conversion efficiency is usually low (Schuster et al., 2009). ORC is new and has been seldomly studied in composting systems. It was reported that the ORC could be a suitable approach to recover heat in the exhaust air of a MSW composting; in this case, the temperature of exhaust air ranged between 316-340 K while the energetic efficiency ranged between 1.5–11% (Micalea, 2014). Di Maria et al. (2014a) analyzed the possibility of recovering heat from integrated composting and anaerobic digestion of OSW to generate electricity by using ORC. The result shows that combustion of biogas could increase the temperature of the exhaust air of a composting from 340 to 510 K, and increase the electricity production generated by ORC from 1 to 25 kW (Di Maria et al., 2014a). Moreover, combustion of solid fuel could also increase the temperature of exhaust air from 330 to 510 K, and could improve the electricity generation by OCR from 9 to 12 kW (Di Maria et al., 2014b).

The third low-temperature heat recovery technology used for composting is thermoelectric generators (TEGs). TEGs can directly converted the generated heat into electrical energy. TEGs follows the principle of Seebeck effect (Martín-González et al., 2013). TEGs have a long life, high safety, high reliability, and cause no harmful effects on the environment e.g. pollution and noise (He et al., 2015; Zarifi and Mirhosseini Moghaddam, 2020). However, the application of TEGs is limited in power generation due to the low energy conversion efficiency (Liu et al., 2020). It was reported that TEGs combined with composting process could generate a maximum voltage about 11.3 V, a maximum current of 18.5 mA, and a maximum power density of 175 mW/m^2 at a temperature gradient of 20 °C (Rodrigues et al., 2018). Besides, Shangguan et al. (2020) verified that TEGs could generate electricity via the temperature difference between composting and environment; they reported that TEGs could generate over 7 W energy with 8.8–18.6 V voltage under a temperature difference of 40 °C.

4.6. Comparison between different heat recovery technologies

In this study, we introduce two types of heat recovery technologies applied to composting, namely traditional heat recovery technologies and low-temperature heat recovery technologies. Generally, the construction of traditional heat recovery technologies is simple and low-cost. Therefore, traditional heat recovery technologies have been extensively studied in both commercial reactors and pilot scales. Their efficiency varies with the different composting studies. For commercial reactors, technologies with high efficiency are required to recover the generated heat as much as possible. For pilot studies, the construction cost is a key factor determining the types of heat recovery technologies.

Low-temperature heat recovery technologies are limitedly applied to composting because they are relatively new compared to traditional heat recovery technologies. Among all these low-temperature heat recovery technologies, HP can increase the quality of recovered heat, which is advantageous over traditional heat recovery technologies. ORC and TEGs can covert the generated heat to electricity, which is the promising technologies to reuse the heat from composting. As a result, ORC and TEGs gain significant research interest although their energy transfer efficiency is low. Table 8 summarizes the properties of different heat recovery technologies reviewed in this study.

Table 8
Different heat recovery technologies applied to composting.

Technologies	Properties	Application
Water jacket	Low heat recovery efficiency, not suitable for big scale reactors	Small scale reactors
TBP	Easy to build; low cost; labor intensive; tubes can be easily damaged during construction; cannot mix the composting pile after construction; low heat recovery efficiency	Pilot-scale reactors, backyard reactors
HEH	High efficiency; the composting pile can be mixed; has little effect on the temperature of the composting pile; will dry out the composting process	Commercial reactors, pilot reactors
PW	High water recirculation; conservation of the nutrients; the composting pile can be mixed; only valid in composting substrates with big particle size and high porosity	Lignocellulosic biomass composting
HP	Can increase the heat temperature; the composting pile can be mixed; has little effect on the temperature of the composting pile	Commercial reactors; pilot reactors
ORC	The output energy is electricity; low maintenance and personnel cost; the composting pile can be mixed; has little effect on the temperature of the composting pile; low energy transfer efficiency	Commercial reactors
TEGs	Low maintenance cost, the output energy is electricity, no greenhouse gasses emission; low energy transfer efficiency; does not affect the pile temperature	Commercial reactors

Note: TBP = tube buried in the pile; HEH = heat exchanger in the headspace; PW = percolation water; HP = heat pump; ORC = organic Rankine Cycle; TEGs = thermoelectric generators.

5. Heat utilization from composting: challenge and outlook

After recovery, the heat is ready for utilization. Without temperature-increasing technologies like heat pump, the outlet temperature of heat generated from composting generally ranges from 20 to 80 °C, depending on different composting processes and heat recovery devices. This temperature range fits well for building applications such as air heating, floor heating, and domestic hot water service (Kimman, 2019; Tucker, 2006; Walther et al., 2016). Besides, the heat from composting could be used for bath/swimming pool (Bajko et al., 2018; Loggia et al., 2019; Pain, 1972), and fishing pond (Seki et al., 2014). Often, a storage tank is needed to buffer the temperature and energy demand (Smith et al., 2017).

Heat from composting can also be used in agriculture and horticulture. The easiest utilization of the generated heat is the hotbed, which is commonly used in cold regions. The idea of employing the hotbed is not new (Ernst, 1990). Farmers in northern China used composting as hotbed to increase the yield of crops over 2000 years ago (Brown, 2014). It was also reported that using a composting of kitchen waste and garden waste as a hotbed in north-eastern Poland could accelerate radish yield by 5 days; the residue compost could be effectively used for garden purpose (Neugebauer, 2018). In addition, composting can also be used for greenhouses, because the generated CO_2 and heat from composting is amendable to greenhouses. It was reported that the heat generated from composting could meet the heat demand for a greenhouse to grow food all year long (Gilson, 2009). Moreover, the greenhouse supported by a composting reactor could improve the yields of celery, leaf lettuce, stem lettuce oily sowthistle, and Chinese cabbage by 87%−270% due to direct CO_2 fertilization (Jin et al., 2009). In addition to greenhouses, the heat generated from composting could be used for brooding chicken (Roland Mote and Griffis, 1982).

Heat from composting can also be used to heat other facilities that require moderate temperatures. It was reported that composting could be used to heat an anaerobic reactor. (Cheng et al., 2016). Smith (2016) also reported that heat from a composting could warm three 26,500-L anaerobic digester tanks and maintain temperatures at 38 °C. Besides anaerobic digestions, the generated heat from composting could be used for melting snow and ice in winter (Allain, 2007) and dehydrating sludge (Rada et al., 2014). The heat generated from composting, especially in commercial scale reactors, has great potential for various applications.

Heat reuse can be attractive for saving energy and creating economic and environmental benefits if the heat source and the heat demands are close to each other (Irvine et al., 2010; Rada et al., 2014), given the fact that the global energy demand is increasing rapidly. However, there are some challenges which limit its application and requires future research. First of all, the heat production rate is usually dynamic during the composting due to the high heterogeneity of the OSW. For example, lignin degraders usually grow best between 35–50 °C (Tuomela et al., 2000), while temperature higher than 55 °C is suitable for manure composting (Li et al., 2019; Miyatake and Iwabuchi, 2005). The dynamic heat production rate makes the controlling of heat extraction difficult: insufficient heat extraction from composting will over-heat the temperature of composting pile, while too much heat extraction will cool the composting pile which can inhibit the degradation process. Moreover, although the heat production rate is high in the mesophilic phase and thermophilic phase, there is still a lot of heat generated in the cooling phase and maturation phase. Future work could also focus on extending heat recovery and reuse for longer than the first two phases (Nwanze and Clark, 2019).

Secondly, a thermophilic stage for at least three days is necessary for pathogen killing and risk elimination (Burge et al., 1978; Qian et al., 2016). The heat recovery may not occur during the thermophilic stage to guarantee the safe disposal of compost. Although many articles relating to heat reusing have been published, the study on the relationship between the heat recovery and the risk elimination remains unknown. This is important considering the safety of using the compost.

Finally, although heat has been reused to various applications, there is still a knowledge gap between scientific work and actual implementation. Research should be paid on the economic, technological and environmental analysis of reusing heat from composting. It was reported that reusing heat from composting can save both organic carbon (remained in the soil as humus) and cost when comparing it to some other green technologies (solar thermal panels and geothermal plant) and traditional technologies (pellet combustor and natural-gas condensing boiler) (Malesani et al., 2021). However, the methods and technologies reviewed in this study should also be included to get more detailed analyses. Besides, the TEGs and ORC deserve more research attention as they could deliver electricity instead of heat.

6. Conclusion

Heat from composting has gained increasing interest as it can help meet the energy demand and reduce the pressure of global warming. This review article is the first review paper that discusses the advantages and disadvantages of different methods regarding to the heat potential estimation, heat production estimation, and heat recovery. Moreover, this work summarizes different utilization of heat generated from composting and gives a prospect to the future research. The result of this review is useful to understand, design and operate different composting systems as well as improve their heat performance.

Composting substrates generally consists of four OSWs namely food waste, lignocellulose waste, manure waste and sludge waste. These four OSWs have high heating values, which makes composting a process with high potential of energy source. The heating values can be measured by using calorimetric technologies and estimated by empirical analysis such as ultimate analysis, proximate analysis, and composition analysis. The calorimetric technologies, such as bomb calorimeter, are sophisticated, time consuming and costly, and requires the special set-up, measurement and calculation process. The empirical methods are much easier and cheaper compared to the bomb calorimeter. However, their accuracy is heavily dependent on the number of samples used for estimation.

Different methods estimating actual heat production from composting are comprehensively summarized and discussed. The degradation method is widely used to describe the composting process adequately. However, the degradation method must be adjusted to different composting conditions to get a better prediction of heat production. O_2 method is easy and simple. It can be measured continuously to illustrate the composting process. O_2 method has been extensively applied both on big scale reactors and small-scale reactors. Another method to calculate the heat production during composting is by monitoring the heat balance. The heat balance method, which measures the heat balance components other than heat production, is suitable for pilot scale and commercial scale reactors because the heat monitoring data is only valid at large scale reactors. Moreover, the CO_2 evolution method, temperature method, and initial and final heating value method are also discussed in-depth.

We also summarized and discussed different heat recovery methods from composting. Water jacket method has low heat transfer efficiency and is only suitable for the small-scale reactors. Tube buried-in pile method collects the heat from the compost pile. This is commonly used in reactors with long retention time. Heat exchanger in the exhaust air is most common in big scale reactors. It has high heat recovery efficiency because it can collect the latent heat. For the composting of wood chips, the water percolation method is demonstrated because it mainly used for composting which has large particle size and high porosity. Low temperature heat recovery technologies have also been developed to recover from composting. Heat pump can increase the heat from composting both in quality and quantity. ORC and TEGs have low energy transfer efficiency but the output energy is electricity, which has wide utilization.

Recovering heat from composting is usually used for building applications, such as hot water service, floor heating and wall heating. Moreover, the heat can be used in agricultural or horticulture field to increase the crop yield as hotbeds and greenhouses. Exploring other application of the heat from composting, given its characteristic, is also of use and interest. Heat reusing can be attractive for energy-saving, economic effects and environmental protection if the heat source and the heat demanding object are close to each other.

Regarding prospect, we expect to work on investigating the effect of dynamic heat production rate on the controlling of heat extraction. In addition, there is still a gap exists regarding the relationship between heat reuse and the risk elimination. Finally, research regarding to the economic, technological and environmental analysis of reusing heat from composting also need to be addressed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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