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Greenhouse gas emissions from municipal solid waste with a high organic fraction under different management scenarios

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ABSTRACT

Waste management is a major source of greenhouse gas (GHG) emissions and provides an opportunity to reduce carbon emissions that has yet to be fully exploited. The total GHG emissions in the waste management sector in China is quite different from that in developed countries, mainly due to the high biodegradable fraction (almost 60–70%) of municipal solid waste (MSW). Based on the above characteristics of MSW and its current and future management strategies, five typical scenarios were modeled by the EaseTech software to compare GHG emissions under different scenarios. These strategies were evaluated by life cycle assessment (LCA) and sensitivity analysis. The two scenarios of landfilling, either with LFG flaring or with LFG to energy, would cause very high GHG emissions (259.5 $kgCO_2$-Eq/t and 169.0 $kgCO_2$-Eq/t, respectively) due to the rapid degradation and low efficiency of landfill gas (LFG) collection. Incineration with energy recovery would lower total GHG emissions (−17.5 $kgCO_2$-Eq/t) substantially. However, the auxiliary fuel needed would offset its environmental benefit. Two scenarios, anaerobic digestion (AD) of the source-separated organic fractions and residue landfilling, and AD of the source-separated organic fractions and incineration of the fractions with high calorific value, followed by residue landfilling, would result in significant carbon sinks (−27.7 $kgCO_2$-Eq/t and −54.8 $kgCO_2$-Eq/t, respectively). From the perspective of GHG emissions reduction, the optimum technical route of MSW in China would be AD of the source-separated organic fractions, incineration of the fractions with high calorific value, followed by residue landfilling.

1. Introduction

GHG emissions have grown very rapidly in China, from 2.5 t CO_2/y per capita in 1996 to 7.6 t CO_2/y per capita in 2013, according to the World Bank (The World Bank, 2016). At the Paris conference on climate change in 2015, the Chinese government committed to a decrease in the unit gross domestic product (GDP) carbon dioxide emissions of 60–65% by 2030 relative to levels in 2005. Based on European Union (EU) figures that the waste management activities alone could potentially account for 18% of the 2012 Kyoto GHG reduction target set for the original 15 EU member states (International Solid Waste Association, 2011), there is an urgent need to exploit the potential of GHG reduction by managing municipal solid waste (MSW) treatment strategies.

At present, 62.9% of MSW is buried in sanitary landfills, and the remaining 34.9% is burned in incinerators (State Statistical bureau, 2015), and these are the two main waste management strategies expected to prevail by 2020. GHG emissions vary significantly among different disposal methods (Mahmoudkhani et al., 2014; Woon and Lo, 2014). Comparing the reduction in GHG emissions in real scenarios of MSW treatment in eight cities in Vietnam, Thanh and Matsui (2013) reported that the highest GHG emissions occurred from open dumps, and that incineration with energy recovery was the most suitable alternative for treating waste. Cherubini et al. (2009) obtained net GHG emissions per ton of MSW treatment processes in Rome, Italy and reported that the lowest emissions were from the organic component of anaerobic digestion (AD) after sorting. Bernstad and la (2012) reported that incineration, AD and composting were the optimal technologies for MSW treatment. In addition, a comparison of the influence of various parameters on GHG emissions using LCA revealed that MSW composition is a key factor directly affecting GHG emissions from different MSW treatment strategies. Even when the same treatment was used, GHG emissions differed due to differences in MSW

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components and operation parameters (Bernstad and la, 2012).

Compared with developed countries, in China, MSW has both a high organic fraction (60–70%) and high moisture content (MC; > 50%), especially in small- and medium-sized cities (Nie et al., 2000; Yang et al., 2013). The contribution to the greenhouse effect from landfills is significant because of the fast decomposition rate of the organic fractions and low gas collection efficiency in landfills where the MSW is stored initially. Furthermore, since the MSW has a high MC and lower heating value (LHV), the net energy recovery rate is low, and the construction of facilities for the treatment of leachate would be necessary. Hence, the benefit of MSW with incineration (MSWI) is compromised. Overall, these characteristics of MSW in China lead to significantly higher GHG emissions from MSW treatment in China compared with developed countries. Based on a comparison of GHG emissions in cities in China and Europe, a similar conclusion was drawn by Yang et al. (2012), who reported that the fossil carbon fraction (FCF) and LHV were key factors in managing GHG emissions.

However, there have been few studies on GHG emissions from the disposal of MSW with a high organic fraction, and even fewer that assessed the key parameters related to the treatment processes. To investigate the suitable MSW treatment strategy to minimize GHG emissions, based on the characterizations of MSW and current treatment processes, five typical treatment scenarios (landfilling with LFG flaring; landfilling with LFG to energy, incineration with energy recovery, AD of the organic fractions and residue landfilling; and AD of the organic fractions with incineration of the high calorific value components (HCVCs) followed by residue landfilling) were modeled using the EaseTech software, developed at the Technical University of Denmark (DTU, 2017). The first three scenarios represent the current mainstream MSW disposal methods, and the latter two scenarios represent the direction of future development in MSW treatment. The changes in GHG emissions were compared among these waste management strategies using LCA, and key parameters were examined using sensitivity analysis.

2. Methods

2.1. MSW characteristics

MSW samples were collected from three sampling points in a medium-sized city in China, and various components were measured once a month for an entire year (Table 1). The initial MC was 59%, and the LHV was 3250 MJ/t. Based on a comparison with values reported in previous studies in other cities from different regions of China (Li, 2012; Cheng, 2014; Gu et al., 2012), this city was representative of MSW with a high organic fraction. In addition, the FCFs were determined in each sample from the EaseTech database and the recommended value by the Intergovernmental Panel on Climate Change (IPCC) (Eggleston et al., 2006).

2.2. Modelling tools

LCA is a systematic methodology suitable for evaluating the GHG emissions from MSW disposal. One ton of wet MSW was used as the functional unit processed through all treatment scenarios. The IOS 14040s (ISO, 2006a, 2006b) standards were abided and the EaseTech was applied to calculate the material flow and GHG emissions. Compared with other generic LCA softwares such as Simapro and Gabi, the main advantage of EaseTech was that material flow modelling of different MSW fractions was incorporated in LCA, and the computing method was elaborated in cited reference (Clavreul et al., 2014). As a result, EaseTech (its predecessor Easewaste) was widely used for performing LCA in MSW management (Laurent et al., 2014). Based on mass and energy balance, the variables of resources, energy consumption and GHG emissions for each process were calculated and the coefficients within and between these processes were stated in section 2.3. The contributions of different gases to the greenhouse effect was obtained from the literature (Ortner et al., 2013). Several previous studies have shown that the greenhouse effect contributions related to the collection and transportation of waste are generally insignificant compared with the entire treatment process (Tan and Khoo, 2006; Vergara et al., 2011), and there is substantial variation in the collection methods and transportation distances among cities. Therefore, these two aspects were excluded from the scope of this study. The one-factor-at-a-time sensitivity analysis (each time the value of a single parameter was increased or decreased by 10% and the change in total GHG emissions were observed) was performed to investigate the results and identify the most sensitive parameters influencing the results of the LCA.

2.3. Scenarios development

A flow chart was devised of five typical disposal scenarios for current mainstream MSW disposal methods and expected future treatment systems, and the system boundaries were defined inside the frame boundaries (Fig. 1).

Scenario 1:. Landfilling with LFG flaring (Fig. 1a).

Currently the most common method of dealing with MSW in China, very large numbers of this type of landfill site were constructed in the 1990s. LFG production was estimated by first order degradation model, using the degradation coefficient of each component recommended by the IPCC (Eggleston et al., 2006), and the projected collection efficiency increasing from 40% to 80% with increased landfill time. In addition, the surface oxidation efficiency of methane from fugitive emissions gradually increased from 15% to 20%. The electric power consumed in leachate treatment depended on the processing technology: utilization of UASB (Up-flow Anaerobic Sludge Blanket)+MBR (Membrane Bio-Reactor) +NF (Nano-filtration) required 26.9 Kwh/ton (Wang et al., 2009) and was 3–4 Kwh higher when reverse osmosis (RO) was applied for more advanced treatment (Nasr and Sewilam, 2015). To meet the stricter environmental standards, the UASB+MBR+NF+RO process was selected for leachate disposal, so the total electrical power consumption was 30 Kwh/ton.

Scenario 2:. Landfilling with LFG to energy (Fig. 1b).

By 2014, approximately 100 among 604 sanitary landfill sites had been equipped with LFG to energy facilities. The power

Table 1
Composition (as wt %) of municipal solid waste in China.

	Food waste	Paper	Plastic and rubber	Fabric	Green waste	Ash	Ceramic	Glass	Metal
Composition (%)	68.6	5.1	8.0	2.0	1.1	11.3	2.6	2.7	0.6
MC (%)	77.3	36.1	42.3	63.4	46.1	0.0	2.3	3.4	2.5
LHV (MJ/kg)	1.9	9.4	21.5	5.8	9.0	0.0	−0.1	−0.1	−0.1
FCF (%)	0.6	0.5	99.4	19.9	0.0	0.0	0.0	0.0	0.0