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Greenhouse gas emissions from different municipal solid waste management scenarios in China: Based on carbon and energy flow analysis

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ABSTRACT

Waste management is a major source of global greenhouse gas (GHG) emissions and many opportunities exist to reduce these emissions. To identify the GHG emissions from waste management in China, the characteristics of MSW and the current and future treatment management strategies, five typical management scenarios were modeled by EaseTech software following the principles of life cycle inventory and analyzed based on the carbon and energy flows. Due to the high organic fraction (50–70%) and moisture content (>50%) of Chinese municipal solid waste (MSW), the net GHG emissions in waste management had a significant difference from the developed countries. It was found that the poor landfill gas (LFG) collection efficiency and low carbon storage resulted landfilling with flaring and landfilling with biogas recovery scenarios were the largest GHG emissions (192 and 117 kgCO_2-Eq/t, respectively). In contrast, incineration had the best energy recovery rate (19%), and, by grid emissions substitution, led to a substantial decrease in net GHG emissions (−124 kgCO_2-Eq/t). Due to the high energy consumption in operation, the unavoidable leakage of CH_4 and N_2O in treatment, and the further release of CH_4 in disposing of the digested residue or composted product, the scenarios with biological treatment of the organic fractions after sorting, such as composting or anaerobic digestion (AD), did not lead to the outstanding GHG reductions (emissions of 32 and −36 kgCO_2-Eq/t, respectively) as expected.

1. Introduction

Facing the challenge of climate change, China committed to reduce its GHG emissions per unit of gross domestic product (GDP) by 60–65% from 2005 levels in 2030. Meanwhile, the achievement in the original 15 EU member states that waste management activities alone could account for 18% of the 2012 Kyoto GHG reductions target (ISWA, 2011) indicates that there is an urgent need to exploit the potential of GHG reductions of it in China.

GHG emissions vary significantly among different waste management scenarios (Mahmoudkhani et al., 2014). Habib et al. (2013) pointed out that the technology development for incineration as well as the energy and material recovery accounted for significant savings of global warming potential during the past five decades. The LCA has been widely used to systematically evaluate different MSW management scenarios and propose improvements. The previous studies concluded that the critical factors effecting the GHG emissions in different treatment methods were (1) LFG collection efficiency, LFG recovery and the biogenic carbon storage (Manfredi et al., 2009; Liu et al., 2017); (2) the content of fossil carbon in the input waste and the energy conversion efficiency (Astrup et al., 2009); (3) composting process and the utilization of the compost product (Boldrin et al., 2009); (4) energy substitution by biogas recovery, fugitive emission of GHG and the carbon storage donated by digested residue (Moller et al., 2009) as to landfilling, incineration, composting and AD technologies correspondingly.

When conducting the LCA, the LCA software are indispensable in most cases. Basically, they can be divided into two types: one is the generic LCA software like SimaPro and GaBi, another is the dedicated waste system modelling tools such as EaseWaste (Kirkeby et al., 2006), Orware (Eriksson et al., 2002), ISWM-DST (Solano et al., 2002) and etcetera. Gentil et al. (2010) pointed out that the different calculation principles and default parameters built into these software could cause a great difference in the

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calculated results. Therefore, it is necessary to conduct the further material flow analysis, which may provide some fundamental details of the treatment process, rather than just evaluating results presented by the software.

The carbon content in MSW can be divided into biological source carbon (BSC) and fossil source carbon (FSC) according to its origin. The BSC in waste management has a dual character. On the one hand, the CH_4 releases from landfill sites is the most important carbon source, whereas on the other hand, a considerable carbon sink can be formed by the non-biodegradable parts. By field investigation, De la Cruz et al. (2013) thought 35–95% of the BSC in MSW could become the long-term storage carbon in landfills. When FSC is landfilled, its high calorific value leads to a large amount of energy waste, but if it is incinerated, additional GHGs are generated. By carbon flow analysis, the function of each part of the waste treatment system can be expressly distinguished. Moreover, carbon flow analysis is also the basis of an energy flow analysis (Kaufman et al., 2008).

In waste management, there is much concern over how to maximize energy recovery from the treatment processes (Fazeli et al., 2016; Consonni et al., 2011; Smith et al., 2015), which will also influence GHG emissions dramatically (Gentil et al., 2010). Cherubini et al. (2009) proposed that different management scenarios would lead to huge differences in the energy recovery rate and GHG emissions.

By reviewing the LCA literatures on GHG emissions, Bernstad and la Cour Jansen (2012) reported that incineration, anaerobic digestion (AD) and composting all had the potential to be optimal technologies for MSW treatment. Even when the same technology was used, GHG emissions could differ due to the immense diversity of MSW components and operational parameters (Yang et al., 2012). Compared with developed countries, MSW in China has the features of high biodegradable organic fraction and high moisture content (Yang et al., 2013). When landfilling, the high biodegradable organic fraction of MSW will decompose too rapidly to install landfill gas (LFG) collection system in time. Meanwhile, the high moisture content can result in large output of leachate (Yang et al., 2015) and high water level, which will decrease the LFG collection efficiency (Zhan et al., 2015). When incineration, the high moisture content can lead to a poor energy recovery rate, and sometimes, auxiliary fuel is required to sustain the combustion (Zhao et al., 2012). These features of MSW in China makes more fugitive emission of CH_4 in landfilling site and less grid emission substitution in incineration, leading to more GHG emissions from waste management.

We examined GHG emissions for different MSW management scenarios recently (Liu et al., 2017). With quite high biodegradable organic fraction (68.6% food residue) and rather low lower calorific value (LHV, 3250 MJ/t), the MSW was a representative of small and medium cities in China, and fluidized bed incinerator with coal as auxiliary fuel was applied for incineration scenario. The results showed that the incineration scenario exhibited not the best GHG reduction potential. However, in larger cities, MSW tends to contain less food residues and more plastics and paper, resulting in higher LHV and lower moisture. Grate furnace incinerator is much more popular in the larger cities for incineration, with higher energy recovery rate and without the addition of auxiliary coal. This will bring out more GHG reduction advantages, which should be further analyzed.

To determine the carbon and energy flows in each waste management strategy and to identify which mode is more suitable for the treatment of MSW in China as well as the vital factors within each MSW treatment method, based on the national-wide commonness of waste component and treatment technologies, five typical treatment scenarios (landfilling with LFG flaring; landfilling with LFG recovery; incineration; composting of the biodegradable fractions with incineration of the high calorific value components (HCVCs), followed by residue landfilling; and AD of the biodegradable fractions with incineration of the HCVCs, followed by residue landfilling) were modeled using the EaseTech software and following an LCA methodology.

2. Methods

2.1. Methodology

Based on the static composition of MSW and the fundamental principles of the ISO 14040 standards (ISO, 2006a,b), the carbon and energy flow as well as GHG emissions within different treatment technologies were analyzed by the EaseTech software and the specific calculation processes were elaborated in Kirkeby et al. (2006) and Clavreul et al. (2014). The characterized impacts of GHG emissions were referenced to IPCC (2006). One ton of wet MSW was used as the functional unit, and the conversion of elemental carbon (both the BSC and FSC) and energy consumption or recovery in each treatment step were based on mass and energy balance and were calculated by a conversion coefficient and efficiency (Supplementary Table 1). Referenced to ISO/TS 14067 (2013), the long-term retention of BSC in soil was recognized as a carbon sink (means GHG reductions), and the CO_2 returned to the atmosphere from BSC was considered neutral (means no GHG emissions or reductions) in terms of GHG emissions. Differently, the preserved FSC was also classified as carbon neutral, while the CO_2 released from FSC represented a carbon source (means GHG emissions). The CO_2 equivalence of different gases was obtained from Ortner et al. (2013), and the GHG emissions of the Chinese national grid were obtained from Liu et al. (2010).

2.2. MSW characteristics

Considering the MSW components varied in different areas of China, the national average (Zhou et al., 2014) were used for analysis. The average physical and chemical characteristics are shown in Table 1. The initial moisture content was 55%, the LHV was 4875 MJ/t, and the high heating value was 6216 MJ/t. The FSC fraction in each component was determined by the recommended value from the Intergovernmental Panel on Climate Change (IPCC, 2006).

2.3. Scenarios development

The treatment processes and system boundaries (the dashed frames) of the five typical management scenarios were devised in the flow chart (Fig. 1). The first three scenarios represent the current waste management modes, and the latter two represent the emerging modes of MSW management in China. Meanwhile, several previous studies figured out that the GHG emissions generated by the collection and transportation processes are generally insignificant compared with the entire treatment processes (Tan and Khoo, 2006; Vergara et al., 2011), and the collection methods and transportation distances were varied among cities. Therefore, these two aspects were excluded from the scope of this study.

2.3.1. Scenario 1: Landfilling with LFG flaring

This type of sanitary landfill sites were widely constructed in the 1990s and became the most common method of MSW disposing. The first-order degradation model was applied to estimate the annual landfill gas (LFG) production (Nyns and Gendebien, 1993) and the degradation coefficient of each waste component was adopted by the recommended value from the IPCC (2006). The LFG collection efficiency in well-controlled sanitary landfills was

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