Resources, Conservation & Recycling 125 (2017) 98–106

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Environmental performance evaluation of different municipal solid waste management scenarios in China

Yili Liu, Peixuan Xing, Jianguo Liu*

Key Laboratory for Solid Waste Management and Environment Safety, Ministry of Education of China, School of Environment, Tsinghua University, Beijing 10084, China

ARTICLE INFO

Keywords:
Municipal solid waste (MSW)
Landfilling
Incineration
Composting
Anaerobic digestion (AD)
Life cycle inventory (LCI)

ABSTRACT

Currently, the overwhelming majority of municipal solid waste (MSW) has been treated in sanitary landfills and incineration plants in China. In future, with the popularization of separate waste collection, it is logical to treat the biodegradable components using biological treatment technologies. To determine the advantages and disadvantages of each waste management strategy, both life-cycle inventory analysis and impact assessment are applied. The advantages and disadvantages of each waste management strategy is evaluated using environmental performances of these management methods on multi-dimensions as waste reduction, stabilization, material recovery, energy recovery, and greenhouse gas (GHG) reductions. These results showed that the scenarios of raw MSW landfilling would result in minimal waste reduction (34.8%) and stabilization (87.8%) rate as well as significant amounts of GHG emissions (116.7–192.2 kg-CO_2Eq/t). On the other hand, the incineration scenario exhibited significant superiorities on these dimensions with a 79.2% reduction rate, 100% stabilization rate, and 124.3 kg-CO_2Eq/t GHG reduction. Moreover, 1163.1 MJ/t of electricity could be recovered from the incineration process. The unique advantage of these scenarios with separated biodegradable components treated by biological methods was the land application of the biological treated residue. A maximum of 89.3 kg/t or 122.0 kg/t material could be recovered when composting or anaerobic digestion (AD) of the biodegradable fractions with incineration of the high calorific value components (HCVCs), followed by residue landfilling. However, when the waste-generated bio-fertilizer could not be applied by field, these waste management scenarios with classified treatment would yield less competitive benefits in each evaluation dimension.

1. Introduction

According to the "Chinese Statistical Yearbook" (State Statistical Bureau, 2015), in 2015, 191 million tons of municipal solid waste (MSW) were collected and more than 94.1% of it was treated sanitarily. Among the treated part, 63.7% of MSW was disposed of in sanitary landfills, 34.3% was treated in incinerators, and the remaining 2.0% was treated by biological processes in China in 2015 (State Statistical Bureau, 2015).

Compared with the developed countries, Chinese MSW has both high organic fraction (60–70%) and moisture content (MC, > 50%) (Yang et al., 2013), all of which not only make the landfilling operation area the source of great odour and GHG emissions (IPCC, 2001) but also output large volumes of leachate (Yang et al., 2013). Furthermore, due to the high MC and lower heating value (LHV), the net energy recovery rate in Chinese MSW incineration (MSWI) plants is lower than it in developed countries and redundant water drainage in the storage bunker and further treatment is unique and necessary (Chen and Christensen, 2010). Currently, the MSW classified collection and treatment are promoted in many cities. Therefore, the separated biodegradable fractions are to be treated by biological processes, combined with incineration of combustible fractions and landfilling of inert residues. However, the bio-fertilize application of biological treated residue is limited by the poor classification efficiency and the high salt and heavy metal content.

LCA is a powerful methodology for evaluating the environmental impacts for MSW management. Habib et al. (2013) pointed out that the technology development for incineration as well as the energy and material recovery from waste accounted for significant savings of global warming potential during the past five decades. By LCA, Woon and Lo (2016) recommended direct incineration of MSW in Hong Kong. Differently, Rajaeifar et al. (2015) thought the combination of AD with incineration was the most environmental-friendly solution in Iran. Yadav and Samadder (2017) reviewed and reported that incineration, AD and composting were all showing the potential to be the optimal technologies for MSW treatment in different countries. Therefore, the

---

* Corresponding author.
E-mail addresses: ylliu@foxmail.com (Y. Liu), xpx16@mails.tsinghua.edu.cn (P. Xing), jgliu@tsinghua.edu.cn (J. Liu).

http://dx.doi.org/10.1016/j.resconrec.2017.06.005
Received 30 March 2017; Received in revised form 5 June 2017; Accepted 5 June 2017

LCA ought to be carried out according to the local conditions (Laurent et al., 2014) and the analysis results are greatly affected by the characteristics of the waste and the technological parameters in the processes (Minoglou and Komilis, 2013; Nguyen and Matsui, 2013; Martinez-Sanchez et al., 2017). However, limited studies have been conducted to evaluate the strength and weakness of current and future MSW management systems in China.

Moreover, previous LCA studies mainly focus on evaluating the effects, such as global warming potential, acidification potential, eutrophication and etcetera (Cleary, 2009; Yi et al., 2011; Quiros et al., 2015). McDougall and Hruska (2000) pointed out that the systematic approach did not always need to use impact assessment and even inventory data alone was sufficient for an evaluation in many cases. In fact, a LCI analysis to indicate the direct effectiveness of MSW management such as mass or volume reduction, waste final stabilization, energy and material recovery are more helpful for the local authorities to make a decision on MSW management at local level.

The core task of waste management is to reduce the amount of waste and prevent environmental pollution. During the treatment process, optimized resource and energy recovery can be important and positive factors to promote this public welfare industry. Meanwhile, facing the increased challenges of climate change and considering the waste management activities alone realized 18% of the 2012 Kyoto GHG reductions target in the original 15 European Union (EU) member states (International Solid Waste Association, 2011), there is an urgent need to exploit the potential for GHG reductions by MSW treatment strategies.

Therefore, in order to evaluate the environmental performance and clarify the advantages and disadvantages of different treatment routes for MSW characterized with a high organic fraction and moisture content, both life-cycle inventory analysis and impact assessment are applied to calculate the multi-dimensional indicators (i.e., waste reduction and stabilization rate, material and energy recovery rate, as well as GHG reductions in each current mainstream or future feasible scenario). This research provides some insights into the MSW management planning in China and other developing countries with similar waste characteristics, in South and Southeast Asia, Africa and Latin America (SPREP, 2010; The World Bank, 2012).

2. Materials and methodology

2.1. MSW characteristics

The average physical and chemical characteristics of the MSW in China are shown in Table 1 (Zhou et al., 2014). The initial moisture content, LHV, higher value (HHV) is 54.8%, 4875 MJ/t, and 6216 MJ/t, respectively. The fossil source carbon (FSC) fraction in each component is determined using the recommended value from the Intergovernmental Panel on Climate Change (IPCC, 2006).

2.2. Life-Cycle inventory

The ISO 14040 standards (ISO, 2006a, 2006b) are followed and one ton of wet MSW was used as the functional unit in this research. By mass and energy balance in each treatment step, the output and residue, along with GHG emissions can be calculated by the parameters of conversion coefficient and efficiency. In this process, the EaseTech software is applied to modelling the scenarios and calculating the final output and impacts. The specific formulas are elaborated in Kirkeby et al. (2006), Boldrin et al. (2011), Finkbeiner (2011) and Clavreul et al. (2014).

2.3. Evaluating indicators

2.3.1. Waste reduction rate

The waste reduction indicator refers to the mass ratio of the recycled and reduced waste to the raw waste, which can be calculated by (1- the final retained mass in landfill site/the mass of raw MSW) × 100%. The final retained mass in landfill site is divided into three parts: (1) inorganic components, (2) nonbiodegradable organic components in anaerobic condition, and (3) retained water in the landfill body. The anaerobic nonbiodegradable ratio of each waste component is given by Calabro et al. (2015) and Naroznova et al. (2016) and the retention percentage of water is calculated by the field water holding capacity after landfill closure, which was thoroughly studied by Yang et al. (2015).

2.3.2. Waste stabilization rate

The stabilization rate indicator refers to the sum of the percentage of the mineralized and immobilized biological source carbon (BSC), which is calculated by (1- the leakage mass of BSC into the ecosphere/ the mass of BSC in raw MSW) × 100%. Depending on the origin, the carbon contented of the MSW can be divided into FSC and BSC (Sahlin et al., 2007). During the waste management, the BSC is the most active and degradable components and also the precursor of many kinds of gaseous and liquid contaminants. There is a significant positive correlation between the leakage of BSC still in organic form and the emissions of pollutants to both the atmosphere (Tagaris et al., 2003; Gutierrez et al., 2015) and aquatic environment. Therefore, the thoroughness of a waste treatment pathway can be reflected by the stabilization rate of the BSC.

2.3.3. Material recovery rate

The material recovery indicator refers to the mass ratio of the recovered waste relative to the raw waste.

2.3.4. Energy recovery rate

The energy recovery indicator refers to as the ratio of recovered energy to the total energy (HHV) contained in the raw waste.

2.3.5. GHG emissions

The GHG emissions in each treatment scenario is calculated basing on the ISO 14064 standards (ISO, 2006c, 2006d, 2006e). The long-term retention of BSC in soil is considered a carbon sink, while the CO_2 from BSC is carbon neutral in terms of GHG emission quantification. Differently, the preserved FSC is regarded as carbon neutral and the generated CO_2 is a carbon source. Moreover, the GHG emissions from upstream production of electricity are analyzed by Liu et al. (2010a).

2.4. LCA scenarios and parameters

The flow charts and associated system boundaries (dashed lines) of

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

	Food waste	Paper	Plastic and rubber	Fabric	Green waste	Glass	Metal	Ceramic	Ash
Composition (%)	55.9	8.5	12.0	3.2	2.9	5.0	4.6	3.9	7.9
Moisture content (%)	77.3	36.1	42.3	63.4	46.1	3.4	2.5	2.3	0.0
LHV (MJ/kg)	1.9	9.4	21.5	5.8	9.0	−0.1	−0.1	−0.1	0.0
FSC fraction (%)	0.6	0.5	99.4	19.9	0.0	0.0	0.0	0.0	0.0