Resources, Conservation & Recycling 130 (2018) 215–225

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Full length article

Resource impacts of municipal solid waste treatment systems in Chinese cities based on hybrid life cycle assessment

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ARTICLE INFO

Keywords:
China
City
Input-output analysis
Life cycle assessment
Municipal solid waste
Resources

ABSTRACT

Municipal Solid Waste (MSW) management in Chinese cities is a significant challenge. However, the comprehensive resource impacts of MSW treatment systems in Chinese cities are unclear. This study presents a mixed-unit hybrid life cycle assessment for MSW treatment systems. The comprehensive resource impacts of six MSW treatment systems in China are evaluated using this method: (1) landfilling, (2) landfilling with landfill gas utilization, (3) incineration with leachate spray, (4) composting + landfilling, (5) composting + incineration, and (6) incineration with leachate centralized treatment. The results show that composting + incineration has the lowest resource impacts except for raw coal extraction. Reusing by-products of MSW treatment systems can reduce resource extraction of the entire economy. By reusing the by-products, landfilling induces the largest extraction of fossil fuels and biomass, whereas landfilling with landfill gas utilization induces the largest extraction of mineral ores. Improving the diesel efficiency of the collection and transportation process, increasing by-product recovery efficiency, and decreasing moisture content of MSW have significant impacts on reducing resource impacts of MSW treatment systems. We also observed trade-offs in resource impacts of different MSW treatment systems. Compared to landfilling, landfilling with landfill gas utilization can reduce the induced fossil fuel extraction but increase the induced metal ore extraction. We observed similar situation when comparing incineration with leachate spray with composting + landfilling.

Findings of this study provide scientific foundations to improve the resource efficiency of MSW treatment systems in Chinese cities. They also provide insights into the MSW management in other countries.

1. Introduction

Managing Municipal Solid Waste (MSW) in a sustainable manner is challenging in cities around the world (Vergara and Tchobanoglous, 2012). This issue is especially severe in Chinese cities due to its rapid urbanization and economic development. The annual MSW generated in China is expected to reach 510 million tonnes by 2025, nearly twice the MSW of the United States (Hoornweg and Bhada-Tata, 2012). The treatment of MSW, directly and indirectly, uses resources such as direct energy use in MSW treatment processes and indirect metal ore use for MSW treatment buildings. China, as the largest resource extractor (Liang et al., 2014) and the largest energy consumer (BP, 2016), faces a high risk of resource shortage. Thus, it is necessary to improve the resource efficiency throughout the life cycle of MSW treatment systems. Properly accounting for resource impacts of MSW treatment systems is the scientific foundation for policy decisions to improve their resource efficiency. Resource impacts of MSW treatment systems in this study include direct and indirect resources used throughout the life cycle of MSW treatment systems.

Life Cycle Assessment (LCA), which considers direct and indirect environmental impacts of a product or service (ISO, 2006), has been widely used to evaluate environmental impacts of MSW treatment systems in China. Existing studies implemented for China mainly focus on the impacts of global warming (Dong et al., 2014; Liu et al., 2017; Zhao et al., 2011; Zhao et al., 2009) and energy use (Chi et al., 2015; Dong et al., 2014; Hong et al., 2010) of MSW treatment systems. For example, our previous study evaluated greenhouse gases (GHG) emissions and GHG mitigation potential of MSW treatment systems in Tianjin City (Zhao et al., 2009). We also observed trade-offs between economic benefits and GHG mitigation of MSW management systems (Zhao et al., 2011). Dong et al. (2014) and Chi et al. (2015) assessed energy–environmental–economic performances of various MSW management systems in Hangzhou City. However, the comprehensive resource impacts of MSW treatment systems in China, including induced

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https://doi.org/10.1016/j.resconrec.2017.12.004
Received 26 July 2017; Received in revised form 27 November 2017; Accepted 2 December 2017

Nomenclatures

A	Direct requirement coefficient matrix
AP	Agricultural products
CP	Crude petroleum
$c_{i,k}$	The contribution of the i^{th} direct input to the k^{th} resource impact of a functional unit
E	Resource intensity matrix
EEIO	Environmentally extended input-output
FM	Ferrous metal ores
FP	Forestry products
f	Functional unit
I	An identity matrix
i	Direct input of MSW treatment process is denoted as subscript i
k	Resource impact is denoted as subscript k
LCA	Life cycle assessment
MSW	Municipal solid waste
NFM	Non-ferrous metal ores
NG	Natural gas
NM	Non-metallic mineral ores
Q	Satellite account representing resource extraction
RC	Raw coal
RI	Resource impacts
T_k	Column vector indicating the k^{th} resource impact induced by direct inputs
$t_{i,k}$	An element of T_k, the k^{th} resource impact induced by the i^{th} direct input
U	Intermediate transaction matrix of the use table
V	Intermediate transaction matrix of the make table
V_d	Diagonal elements of V
V_{od}	Off-diagonal elements of V

extraction of biomass, mineral ores, and fossil fuels (Eurostat, 2001), are not well characterized in existing studies. In addition to energy sources considered in existing studies, biomass and mineral ores, especially metal ores (Graedel et al., 2012), are critical essential resources to human well-beings. Investigating more comprehensive resource impacts of MSW treatment systems can provide additional information for improving their resource efficiency.

Moreover, life-cycle environmental impacts of MSW treatment systems have been insensitively studied in the United States (Morris, 2010; Thorneloe et al., 2007; Weitz et al., 2002), European countries (Ekvall et al., 2007; Emery et al., 2007; Eriksson et al., 2005; Kirkeby, 2006), and other developing countries (Aye and Widjaya, 2006; Leme et al., 2014). However, most of these studies overlooked the resource impacts of MSW treatment systems. This study can provide foundations for the selection and improvements of MSW treatment systems in other countries, in terms of resource impacts.

The process-based LCA is popularly used in existing LCA studies of MSW treatment systems. However, it can track only limited layers of supply chains and has truncation error (Matthews and Small, 2000; Suh, 2004). The truncation error can sometimes induce large uncertainties in results and probably mislead policy decisions (Mattila et al., 2010). A hybrid LCA integrating a process-based LCA and an Environmentally Extended Input-Output (EEIO) model can extend the system boundary of the process-based LCA and provide a more accurate assessment (Suh, 2004). It is an attractive tool to track the resource flows along supply chains. However, there are seldom studies on the hybrid LCA of resource impacts of MSW treatment systems.

This study fulfills the above knowledge gaps by evaluating the comprehensive resource impacts of MSW treatment systems in Chinese cities based on a hybrid life cycle assessment. The resource impacts in this study include the extraction of biomass (agricultural and forestry products), fossil fuels (raw coal, crude petroleum, and natural gas), and mineral ores (ferrous metal ores, non-ferrous metal ores, and non-metallic mineral ores). Six typical MSW treatment systems in Chinese cities are compared: landfilling, landfilling with landfill gas utilization, incineration with leachate spray, composting + landfilling, composting + incineration, and incineration with leachate centralized treatment. Contribution analysis and sensitivity analysis are conducted to identify key inputs and hotspots for improving MSW treatment systems. Findings of this study provide scientific foundations to improve the resource efficiency of MSW treatment systems in Chinese cities. They also provide foundations for reducing resource impacts of MSW treatment systems in other countries.

2. Methods and data

2.1. Hybrid LCA

Traditional process-based LCA has truncation error, because it only tracks limited layers of upstream environmental impacts (Matthews and Small, 2000; Suh, 2004). The EEIO model captures all the supply chains within an economy and can extend the system boundary of traditional process-based LCA (Matthews and Small, 2000). Hybrid LCA was proposed to combine traditional process-based LCA with EEIO models (Liang et al., 2012b; Matthews and Small, 2000; Wiedmann et al., 2011). It can capture the bottom-up inventory information of each process and covers the full system boundary of economic systems. Meanwhile, hybrid LCA also inherits some uncertainties of EEIO models such as the aggregation of industrial sectors, the age of EEIO database, and assumptions associated with EEIO models (Hawkins et al., 2007; Matthews and Small, 2000). Nevertheless, the advantage of complete economic system boundary of the hybrid LCA facilitates its wide applications. Hybrid LCA has been widely used to assess environmental impacts of commodities and technologies such as wind power generation (Wiedmann et al., 2011), solid waste treatment (Inaba et al., 2010; Liang et al., 2012b), wastewater treatment (Lin, 2009), and biofuel production (Acquaye et al., 2011; Liang et al., 2012a, 2013; Malik et al., 2015).

EEIO models based on input-output tables are usually used for hybrid LCA. However, hybrid LCA of MSW treatment systems requires EEIO models based on make-use tables. Make-use tables have the advantage of explicitly accounting for secondary products and by-products (Miller and Blair, 2009). MSW treatment systems are complex and multi-functional (Zhao et al., 2009). MSW treatment systems have two different types of products: MSW treatment services (primary product) and by-products such as recovered energy and materials. These products have different sector classifications. A sector of input-output tables (usually in commodity-by-commodity form) can only describe a set of homogeneous commodities. In contrast, make tables (in industry-by-commodity form) and use tables (in commodity-by-industry form) can describe multiple types of heterogeneous commodities related to an industrial activity (Appendix A). Thus, EEIO models based on make-use tables are suitable for hybrid LCA of MSW treatment systems.

The application of a hybrid LCA in this study comprises three steps: (1) collecting bottom-up inventory data for each process in MSW treatment systems; (2) incorporating each process into the make-use tables to get a mixed-unit EEIO-LCA model; and (3) calculating resource impacts of MSW treatment systems using the mixed-unit EEIO-LCA model.