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Intensification of municipal solid waste disposal in China

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ABSTRACT

To trace the source attribution of environmental burdens from municipal solid waste (MSW) at the macro level, identify the key factors in environment protection, and explore the involved mechanisms, life-cycle assessment (LCA) was used in this study. The major environmental hazard emissions caused by MSW disposal in China during the last decade were carbon dioxide, methane, mercury, chromium, and arsenic emissions. Environmental benefits varied significantly with the use of alternatives to coal-based electricity generation technologies, indicating that the current MSW-incineration-based electricity generation in China is not absolutely cleaner than the advanced coal-based electricity generation technology. Effective measures to reduce the environmental impact include improving electricity generation efficiency, reducing direct mercury emissions, maximizing the recycling system, providing separate food waste disposal, and optimizing landfill leachate management.

1. Introduction

Municipal solid waste (MSW) is a waste type that comprises everyday items such as food waste, building waste, paper, and plastic that are discarded by the public. Current global annual MSW generation is approximately 1.3 billion t [1], in which approximately 13% is generated from China because of vast urbanization [2]. By the end of 2014, the national MSW generation amount, number of treatment facilities, and harmless treatment rate in China had reached 0.18 billion t, 818%, and 91.8%, respectively. MSW disposal in China is primarily conducted using landfill (65.5%) and incineration (32.5%) technologies. During the last decade, the national MSW incineration rate has dramatically increased because of the importance of MSW reduction in volume. For instance, about 7.9×10^6 and 5.3×10^7 t of MSW incinerated in China were reported for years 2005 and 2014, respectively [2], corresponding to an annual increase of 23.55% in just a span of 10 years. This increasing trend was also observed in Europe and the United States [3]. However, strong public opposition was frequently raised due to a large amount of toxic pollutants (e.g., dust, dioxin, furan, mercury, arsenic, and lead) emitted from MSW incineration [4]. These pollutants emitted from China must be addressed as they may deteriorate the air quality of the Pacific, Arctic, and North American regions [5,6]. To better understand the relationship between MSW disposal and its environmental effects and determine effective approaches to improve the environment at the macro level, it is prerequisit to quantify the current situation (e.g., pollutants, environmental impact, key factors) of MSW disposal in China and explore the links among the consumption, production, emissions and environmental impacts.

LCA can achieve the aforementioned goals by enabling quantifications of individual emission influence on environment. LCA is an internationally standardized method [7] to simultaneously, systematically, and effectively evaluate and identify the environmental inventory, impact, key factors, decisions, optimization, and opportunities for improvement associated with all stages of a product, including all activities from the beginning to the final phase. The system boundary may be chosen arbitrarily depending on the goal and application of research. This condition denotes that the system boundary can either be micro-level [8] or macro-level [9]. Thus, LCA can easily identify the relationship between the major microscopic variable and macroscopic

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environmental effects generated from the targeted system.

The emissions and environmental impacts of MSW incineration and landfill have been extensively studied via LCA in China [4,10], Europe [11], Japan [8,12], and the United States [13]. However, the majority of researchers have focused on on-site case studies and failed to consider the potential environmental impact and the improvement potentials of MSW disposal at the national level [4,8,10,11]. Moreover, most LCAs were unclear as to whether direct air and leachate emissions from MSW incineration and landfill processes were collected from actual field data [4,10,12]. Furthermore, most researchers have been carrying out LCA studies on MSW disposal without considering uncertainty [4,8,10–13]. To address these issues, a bottom-up approach based on actual field data was used to evaluate the source attribution of environmental impact from MSW disposal initiatives at the national level and identify the potential measures for environmental improvement in China. Additionally, the direct key pollutants and environmental performance caused by MSW disposal in China were compared with those in other parts of the world. Finally, the necessity of optimizing the current MSW incineration technology in China was discussed and the human health alert level for bio-energy generated from MSW in China was quantified.

2. LCA methodology

2.1. Evaluation of life cycle inventory at macro level

To evaluate the environmental footprint from MSW disposal at the macro level, a bottom–up approach was employed in this study on the basis of Hong et al. [9] investigation. The bottom–up approach begins with on-site case studies and applied LCA based on ISO standards [7]. The LCA for the commonly used technologies of MSW disposal (i.e., fluidized bed incineration, grate incineration, and landfill with/without biogas utilization) was conducted separately to determine the key factors (i.e., processes and substances) that contribute to the overall environmental burden. Secondly, national, regional, and industrial statistical data were used in replace of the aforementioned key factors obtained from on-site individual data as new inputs. LCHA was re-conducted to determine whether new key factors have been generated. The aforementioned two steps were repeated until no new factor was found. Finally, national and regional statistical data (e.g., MSW generation amount, MSW incineration and landfill rate, and technological transformation) were combined with the above-mentioned newly updated life cycle inventory to carry out LCA at the regional and national level by using Eq. (1). Table 1 shows the list of mathematical symbols and definitions. To confirm and add credibility to the study, uncertainty analysis based on Monte-Carlo simulation was conducted.

$$M_T = I_T + L_T + D = \sum_{R=1}^{n} I_R + \sum_{R=1}^{n} L_R = \sum_{R=1}^{n} A_R \times (aE_a + bE_b + cE_c + dE_d + mE_m) \quad (1)$$

Table 1
Math symbols and meaning of Eq. (1).

Symbols	Meaning
M	MSW disposal
I	MSW incineration
L	MSW landfill
D	MSW dumping
R	Region
T	Total
A	MSW disposal amount
E_a	Emission factor of MSW incineration with fluidized bed incinerator
E_b	Emission factor of MSW incineration with grate incinerator
E_c	Emission factor of MSW landfill with electricity recovery
E_d	Emission factor of MSW landfill with biogas burning
E_m	Emission factor of MSW landfill with biogas direct emission
a	Ratio of fluidized bed incineration and total MSW treatment amount
b	Ratio of grate incineration and total MSW treatment amount
c	Ratio of MSW landfill with electricity recovery and total MSW treatment amount
d	Ratio of MSW landfill with biogas burning and total MSW treatment amount
m	Ratio of MSW landfill with biogas direct emission and total MSW treatment amount

2.2. System boundary

The incineration and landfill of 1 t MSW was selected as the functional unit. System boundaries were set by applying a gate-to-gate approach (Fig. 1). Five scenarios, namely, landfill with biogas direct emission (LD), landfill with electricity recovery (LE), landfill with biogas burning (LB), fluidized bed incineration (FBI), and grate incineration (GI) were included in this study. Rotary kiln incineration technology was excluded in the present study because the market share rate of grate and fluidized bed technologies was more than 97% [14] during the last decade. Both MSW incineration scenarios (i.e., fluidized bed and grate) involve raw materials transport, electricity recovery, MSW storage, MSW incineration (850–950 °C), fume purification with active carbon absorb and bag dedust (dedust rate > 99%), fly ash and slag disposed to landfill, semi-dry desulfurization (desulfurization rate > 80%), and leachate disposal processes. For the fluidized bed system operation, additional processes of coal crash, MSW crash, and coal storage were involved. The remaining three MSW landfill scenarios differ in terms of the process of biogas treatment but resemble one another in terms of MSW compaction, disinfection, and leachate treatment. The carbon dioxide (CO_2) emissions from MSW incineration and landfill were omitted from the inventory because MSW is considered as a biogenic source. Additionally, the infrastructure of each scenario was excluded because it exhibited very low contribution to the overall LCA [11] and there was a lack of detailed information in the present MSW disposal sites. The MSW collection process was excluded as they were common to each scenario.

2.3. Life-cycle impact assessment of MSW disposal in China

Life cycle impact assessment (LCIA) was conducted at midpoint level through the ILCD method, which supports the correct use of the characterization factors for impact assessment [15]. Thirteen midpoint categories (i.e., climate change, ozone depletion, non-cancer effects, cancer effects, particulate matter, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, water resource depletion, and resource depletion) were used in this study. To reduce the geographic variability of toxicity impact categories, LCIA characterization factors for the non-cancer effects, cancer effects, and freshwater ecotoxicity categories, were adopted from USEtox model [16]. The USEtox model, which is currently recommended by European Union and the United States - Environmental Protection Agency for characterization of human health impacts in comparative chemical toxicity assessment, provides a rapid and transparent tool for human health impact assessment via adopting multi-media fate and multi-pathway models to identify the environmental exposure and toxic effects of pollutants [15,17]. The geography, population, food intake, and environmental condition in China were used to adopt the characterization factors involved in USEtox [17] on the basis of the investigations by Li et al. [18] and Chen et al. [19]. Although USEtox 2.0 has been published with default landscape parameters for eastern China on the basis of the research by Shaked [20], the parameters such as temperature, wind speed, food intake rate, rain rate, and landscape for eastern China shown in the research by Shaked S. [21] were

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