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The growing importance of waste-to-energy (WTE) incineration in China's anthropogenic mercury emissions: Emission inventories and reduction strategies

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ABSTRACT

Waste-to-energy (WTE) incineration has been increasingly adopted for municipal solid waste (MSW) disposal in China, which already accounts for nearly 40% of the global installed capacity and electricity generation from WTE. This review identifies the growing importance of WTE incineration as a source of anthropogenic mercury emissions in China, summarizes the mercury control practices at WTE facilities, estimates the inventories of mercury emissions from WTE and those after the implementation of the more stringent air emission standards, and recommends key measures to further reduce the mercury emissions from WTE industry in China. WTE incineration in China was estimated to have a mean current mercury emission factor (EF) of 0.083 g/tonne (with 95% confidence intervals of 0.056–0.116 g/tonne) based on the mercury contents in MSW and the typical removal efficiencies of air pollution control devices (APCDs). The total mercury emissions from WTE incineration were estimated to be around 6.1 tonnes in 2016, and were predicted to reach 10.6 tonnes by 2020 based on its fast growth. The recently adopted more stringent emission standard for mercury can help curb the growth in mercury emissions from WTE incineration, while the gradual implementation of the Minamata Convention on Mercury is expected to contribute to significant reduction in the emissions of mercury from WTE incineration in the long run. Current estimations for mercury emission inventories from WTE incineration in China carry large uncertainty due to the overall scarcity of data. Thus, more work should be conducted to better monitor and quantify the mercury contents in MSW, and the mercury removal efficiencies of APCDs and the emission rates of mercury at WTE facilities. Meanwhile, China also needs to develop effective recycling and waste-sorting programs to divert the mercury-containing waste items from entering the incinerators and thus reduce the mercury emissions while promoting waste disposal by WTE.

1. Introduction

Environmental pollution caused by mercury has drawn great public concerns due to its well-documented toxic, persistent, and bio-accumulative properties [1]. In particular, because of its long-range atmospheric transport, mercury pollution is a global problem affecting both the heavily industrialized areas and the remote regions far away from the emission sources [2,3]. Many studies have been conducted to quantify the emissions of mercury from the major sources and estimate their contributions to the global anthropogenic emissions [4–6]. Thermal power generation, artisanal gold mining, non-ferrous metal smelting, cement production, and waste disposal are well recognized as the important emission sources of atmospheric mercury [7–9]. Globally, stationary fuel combustion is the largest source of anthropogenic mercury emissions, accounting for nearly 65% of the total emissions in 2000 [5]. Meanwhile, waste-to-energy (WTE) is an important mercury emission source in many developed countries with heavy reliance on incineration for waste disposal [10,11]. Although disposal of municipal

Abbreviations: ACI, activated carbon injection; APCD, air pollution control device; CFBC, circulating fluidized-bed combustor; DSI, dry sorbent injection; EF, emission factor; ESP, electrostatic precipitator; FBA, fixed-bed absorber; FF, fabric filter; GDP, gross domestic product; GFC, grate furnace combustor; HQ, hazard quotient; MSW, municipal solid waste; PM, particulate matter; PRD, Pearl River Delta; SCR, selective catalytic reduction; SNCR, Selective non-catalytic reduction; WS, wet scrubber; WTE, waste-to-energy

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solid waste (MSW) only contributes to approximately 8% of the total anthropogenic mercury emissions [7], its importance has been growing quickly due to the increased popularity of WTE in waste management worldwide.

China is the world's largest emitter of anthropogenic mercury, and is responsible for around a quarter of the global emissions in 2000 [5]. Although combustion of coal in thermal power plants and industrial boilers is the most significant source of mercury emissions in China [12,13], the contribution of WTE incineration has become increasingly more important over the past decade [14,15]. With an average annual growth rate of over 40% between 1995 and 2003, WTE has been the industry with the fastest growth in mercury emissions [16–19]. Urbanization is still on-going in China, thus WTE incineration is going to play an increasingly more important role in the country's waste management.

The first WTE facility in China started operation in 1988, while the industry has been growing rapidly since then [17]. WTE was adopted primarily as an attractive waste management option, while the environmental problems brought by the booming WTE industry did not receive much attention. A relatively limited number of studies have investigated the emissions of highly toxic dioxins/furans from incineration of MSW [20–22], and the heavy metal pollution associated with the fly ash produced from incineration [23–25]. The emissions of mercury from incinerators and the control of mercury emissions were well studied in some developed countries, including United States, Japan, and European countries due to the large-scale deployment of waste incinerators since the early 1970s [11,26–29]. In contrast, only very few studies have focused on the emissions of mercury from WTE facilities in China, as the industry was apparently not an important source of anthropogenic mercury emissions [15]. Overall, there is rather poor understanding of the mercury emission inventories from WTE incineration in China, and the industry's contribution to the total anthropogenic mercury emissions in the country. However, given the fast growth in the deployment of WTE facilities nationwide, it is important to understand the emissions and control of mercury from China's rapidly growing WTE industry, the public health risk of the emitted mercury, and develop effective strategies to control the emissions as well.

This review presents an overview on WTE incineration and the associated emissions of mercury in China, and identifies the increasing importance of WTE incineration as an anthropogenic source of mercury emissions. Mercury removal at WTE facilities in China is discussed in light of the speciation of mercury in combustion chamber and flue gas, and the working mechanisms of the major air pollution control devices (APCDs). The inventories of mercury emissions from WTE industry in China and the associated uncertainty are estimated based on critical evaluation of the very limited existing data on mercury contents in MSW from Chinese cities, and the performance of typical APCDs installed at WTE facilities in China. Previous studies have estimated the mercury emissions from WTE incineration in China between 1995 and 2010, while this study estimates the emissions over the period of 2004 and 2020, and predicts the impact of the more stringent air pollutant emission standards on the emission inventories of mercury from the country's WTE industry. The impact of Minamata Convention on Mercury, an international treaty to reduce mercury pollution from the activities responsible for major mercury releases, on the emissions of mercury from WTE incineration is also discussed. Finally, recommendations on the needs to better monitor and quantify the emissions of mercury from WTE, assess the public health risk of the emitted mercury to the neighboring communities, as well as the technological and policy measures in waste management that can be taken to reduce mercury emissions, are made. With urbanization occurring globally, mercury emissions from WTE in the developing countries are expected to grow significantly in the coming decades. Thus, how China disposes of the increasing volume of MSW by WTE incineration and controls the associated emissions of mercury can be valuable lessons to the other parts of the developing world facing similar challenges.

2. Methodology

2.1. Data collection

Studies on MSW disposal by WTE incineration and mercury emissions from WTE facilities in China, along with those in the other countries, were identified using the most popular sources of scientific information, including Web of Science and Scopus. Keywords, including MSW, WTE, incineration, mercury emissions, and China, were searched to retrieve information on the specific subjects. Major Chinese reference databases, such as CNKI (China National Knowledge Infrastructure) and Wanfang Data, were also used to identify studies published in Chinese. Additional data were collected from technical reports published by several international organizations and Chinese government agencies, and Chinese statistical yearbooks.

2.2. Estimation of mercury emission inventories

The mercury emission inventories from WTE incineration was estimated as:

$$E_{Hg} = 10^{-6} M_{MSW}\, EF = 10^{-6} M_{MSW}\, C_{Hg}\, R(1-P_r) \tag{1}$$

where E_{Hg} is the total emissions of mercury from WTE incineration (tonnes/year), M_{MSW} is the total mass of MSW disposed of by WTE incineration each year (tonnes/year), which is well documented in China's national statistics, and *EF* is the emission factor of mercury for WTE incineration (g/tonne). *EF* is determined jointly by the content of mercury in MSW (C_{Hg}, mg/kg), the fraction of mercury released into the flue gas upon combustion (R), which is set at 0.96 based on the literature [26,29,30], and the overall mercury removal efficiency achieved by the APCDs installed (P_r).

The impact of the implementation of the more stringent air pollutant emission standards on mercury emissions from WTE incineration was estimated. According to the mercury emissions from 20 representative WTE facilities before the tightened air pollutant emission standards were implemented [31], and the assumption that all WTE facilities could meet the mercury emission limit of 0.05 mg/Nm^3 after 2016, the average emission factor (EF) of mercury from WTE incineration was estimated to be reduced by approximately 55% to stay in compliance with the tightened mercury emission standard. In addition, the EF of mercury from WTE was assumed to have decreased linearly between 2014 and 2016 due to the gradual implementation of the standards. Finally, the mercury emission inventories from China's WTE industry up to 2020 were predicted based on the projected growth in MSW disposal by WTE incineration.

2.3. Uncertainty analysis

Previous studies have estimated the emission inventories of mercury from WTE incineration in China based essentially on single values of EF established from certain WTE facilities or those in a given region, while the mercury contents in MSW, and the technologies of combustion and pollution control adopted can vary largely across the country. Unfortunately, only very few studies have investigated the EFs of mercury for WTE incineration. As a result, Monte Carlo simulation, which relies on repeated, random sampling to obtain results, was implemented to account for the uncertainty of the mercury content in MSW (C_{Hg}) and mercury removal efficiency achieved by the APCDs (P_r). In the study, C_{Hg} and P_r were assumed to follow normal distributions, and their means and standard deviations were based on the literature data (Fig. 6 and Table 2). During the simulation, values of C_{Hg} and P_r were randomly sampled based on their probability distributions, and were used to calculate the EF of mercury. The probability distribution