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Atmospheric emissions of typical toxic heavy metals from open burning of municipal solid waste in China

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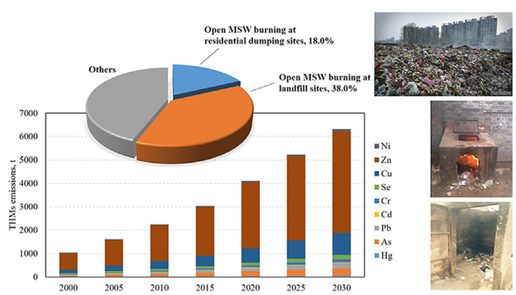
HIGHLIGHTS

- A comprehensive inventory of atmospheric THMs emissions from open MSW burning in China is established.
- Emissions from 361 cities in 2013 are allocated into 0.5° × 0.5° grid cells.
- Future trends of THMs emissions till 2030 are projected with three control scenarios.
- Increasing proportion of waste incineration will result in increasing Hg emission.
- Collaborative effects of all proposals can bring in the largest reduction in THMs emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Municipal solid waste (MSW) contains considerable hazardous components and the widely-distributed open MSW burning in heavily-populated urban areas can cause direct exposure of hazardous materials to citizens. By determining the best available representation of composition-varying and time-varying emission factors with fuzzy mathematics method and S-shape curves, a comprehensive atmospheric emission inventories of 9 typical toxic heavy metals (THMs, e.g. mercury (Hg), arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), selenium (Se), copper (Cu), zinc (Zn), and nickel (Ni)) from open MSW burning activities in China is established during the period of 2000–2013 for the first time. Further, the emissions in 2013 are allocated at a high spatial resolution of 0.5° × 0.5° grid by surrogate indexes. The results show that 9 typical THMs emissions from open MSW burning are estimated at 21.25 t for Hg, 131.52 t for As, 97.12 t for Pb, 10.12 t for Cd, 50.58 t for Cr, 81.95 t for Se, 382.42 t for Cu, 1790.70 t for Zn, and 43.50 t for Ni, respectively. In terms of spatial variation, the majority of emissions are concentrated in relatively developed and densely-populated regions, especially for the eastern, central and southern regions. Moreover, future emissions are also projected for the period of 2015–2030 based on different scenarios of the independent and collaborative effects of control proposals including minimizing waste, improving MSW incineration ratio, and enhancing waste sorting and recycling, etc. The collaborative

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effect of the above proposals is expected to bring the most effective reduction to THMs emissions from open MSW burning in China except for Hg. The results will be supplementary to all anthropogenic emissions and useful for relevant policy-making and the improvement of urban air quality as well as human health.

1. Introduction

Open burning is the disposal behavior of solid waste by uncontrolled combustion in open areas or in barrels. Due to its simpleness and convenience, open burning is a common disposal way of municipal refuse, construction waste, agricultural residues, etc. in urban and rural areas, besides landfill, composting treatment, and incineration. Compared with rural waste burning, the small-scale, widely-distributed open burning of municipal solid waste (MSW) in urban areas deserves highlighted attention since metropolitan areas are heavily populated. The environmental effects and health hazards brought by open MSW burning have become a serious problem not only faced by the developed countries, but also by the developing countries represented by China (Lundin et al., 2013; Wiedinmyer et al., 2014).

With the rapid development of industrialization and urbanization, significant amounts of solid waste have been produced in China and the annual yield of MSW has exceeded 0.3 billion tons (NBS, 2015). No other countries have ever experienced such a large and fast increase in solid waste quantities that China is now facing (Tian et al., 2013). Although prohibited explicitly in China's Law on the Prevention and Control of Atmospheric Pollution, the scenes of open waste burning are frequently spotted, especially in urban-rural conjunctions or urban villages of small towns, and the proportion is reported to be nearly 30% (Wiedinmyer et al., 2014).

Among almost all waste components, there is a certain amount of toxic heavy metals (THMs), such as Hg, As, Pb, Cd, Cr, etc (Hasselriis and Licata, 1996). THMs can not be degraded by microbes and conversely could enrich easily in the organisms, leading to reproductive barriers, developmental disorders, and pathological alterations in organs and tissues, and even death as a worse result (Tong et al., 2000; Chowdhury and Dhundasi, 2009; Thomas et al., 2009; Tchounwou et al., 2012). Due to the defection in waste sorting and recycling systems, the content levels of THMs in MSW are found to be higher in China compared with other countries (Kong et al., 2010).

It has been reported that during the low-temperature combustion processes of open MSW burning, Cr has a weaker volatilization rate of less than 10% and is more likely to remain in the bottom ash while As and Pb have a moderate volatilization rate of nearly 50% and 30%, respectively (US EPA, 2001). For volatile elements such as Hg and Cd, nearly 80% and 65% of the totals are released into the atmosphere with smoke and fly ash, respectively (see Fig. S1 in Supporting Information (SI)). Although the absolute amount is small, the THMs content in suspended particulate dust is still significant (Yoo et al., 2002; Park et al., 2013) and THMs particles in the atmosphere have become one of the major environmental and health concerns in urban areas in China (Hu et al., 2014; Liu, 2014).

Different from MSW incinerators, open burning is rarely considered in regional-scale and global-scale emission estimations of air pollutants except for a few studies (Bond et al., 2004; Fiedler, 2007; Park et al., 2013; Wiedinmyer et al., 2014). In recent years, researchers have began to focus on the atmospheric emission characteristics of THMs, and a series of multi-scale emission inventories have been established for anthropogenic sources in China (Pacyna and Pacyna, 2001; Tian et al., 2012a, 2012b; Cheng et al., 2015; Streets et al., 2005; Zhang et al., 2015). However, the contribution of open MSW burning has not yet been included in all these studies. In this paper, a comprehensive inventory of 9 typical THMs (Hg, As, Pb, Cd, Cr, Se, Cu, Zn, and Ni) that rank among the priority metals with great public health implication due to their potent toxicity is presented with temporal and spatial resolutions from open MSW burning in China. The uncertainties during the emission estimation are assessed with Monte Carlo simulation. In addition, future emissions for the period of 2015–2030 are projected based on different scenarios and proposals for further prevention and control of open MSW burning are also put forward.

2. Methodology and data sources

A "bottom-up" methodology is applied to estimate the atmospheric emissions of 9 THMs from open MSW burning in 361 cities in China. The emission inventory is compiled by using the following equations:

$$E_{T,j} = \sum_i E_{i,j} \tag{1}$$

$$E_{i,j} = B_i \times EF_{i,j}/10 \tag{2}$$

where E_T is the national total of the atmospheric emissions of Hg, As, Pb, Cd, Cr, Se, Cu, Zn, or Ni from open MSW burning, t/yr; E_i is the annual emission of THMs in administrative city i, t/yr; B_i is the amount of MSW burned in city i, 10^4 t; EF is the emission factors (EFs) of THMs emitted per unit of waste burned, g/kg; j stands for the type of THMs.

$$B_i = B_{res,i} + B_{ldf,i} = P_i \times M \times K_i \times (R + L) \times T_i \times B_{frac} \tag{3}$$

$$K_i = \sqrt{\frac{IC_i \times 361}{\sum_{i=1}^{361} IC_i}} \tag{4}$$

$$T_i = \sqrt{\frac{\sum_{i=1}^{361} TR_i}{TR_i \times 361}} \tag{5}$$

B_i represents the sum of the amount of MSW burned at residential dumping sites (B_{res}) while B_{ldf} represents that burned at landfill sites (B_{ldf}) in city i, MSW burned in incinerators or other combustion systems are excluded in the evaluation; P_i is the urban population of city i, 10^4; M_i is the per capita generation rate of MSW in city i; M represents the national averaged per capita MSW generation rate, t/capita/year; partition coefficient K_i and T_i are introduced to quantify the diversity of MSW generation rate and the fraction of open burning of different cities under different economic levels, which are achieved by the function of the per capita disposable income of urban households (IC) and treatment rate of consumption waste (TR) of city i, respectively; R and L stand for the fraction of MSW burned at residential dumping sites and landfill