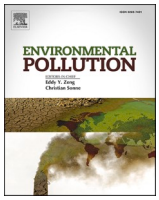
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Air pollutant emissions and reduction potentials from municipal solid waste incineration in China☆

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ABSTRACT

China fully implemented the new emission standards in 2016 to further reduce the emissions of air pollutants from the municipal solid waste (MSW) incineration industry; however, the implementation effect of the new standards remains unknown. This study developed the first nationwide air pollutant emission inventory of MSW incineration plants in China based on the measured concentration data from China's continuous emissions monitoring systems (CEMS) network, and activity level data from the China Urban Construction Statistical Yearbook, to evaluate the effectiveness of implementing the new emission standards and estimate the future reduction potentials. Our results demonstrated that the overall standard-reaching proportions of particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxide (NO_X), hydrogen chloride (HCl) and carbon monoxide (CO) were 98.8%, 99.3%, 99.4%, 99.4% and 97.6%, respectively, by comparing with the corresponding concentration limits of new emission standards. The total emissions of PM, SO_2, NO_X, HCl and CO from 412 MSW incineration plants in 2019 were 1.9, 6.2, 50.8, 4.3 and 6.6 kt yr^{-1}, respectively, which is 33.6–75.8% lower than those in 2015, mainly due to the sharp decrease in emission factors. Pollutant emission hotspots were mainly concentrated in eastern and central and southern regions with large populations and well-developed economies. The analysis of future scenario results shows that despite the continuous increase of MSW incineration amount in the future, if the government strengthens pollutant emission standards and comprehensively implements waste sorting, total emissions and emission factors of air pollutants could be further reduced by 25.8–72.7% and 59.8–81.2%, respectively, by 2050. These findings provide helpful insights into future policymaking and technology selection for China and other countries seeking to reduce pollutant emissions from the MSW incineration industry.

1. Introduction

As the largest developing country in the world, China has produced a considerable quantity of municipal solid waste (MSW), which is closely related to the rapid economic development, accelerated urbanization process and improvement of living standards (Zhang et al., 2010; Havukainen et al., 2017; Chen, 2018; Wang et al., 2021). From 1980 to 2019, MSW production increased rapidly with an annual growth rate of 5.4% (MHURD, 2020; Bo et al., 2022). In 2019, Chinese MSW production reached an astonishing 242 million tons, and approximately 51.6% of provinces or municipalities produced more than 6 million tons of MSW yearly (MHURD, 2020). Furthermore, the proportion of MSW incineration in China is planned to increase to more than 65% by 2025 (NDRC, 2021) and even 100% in specific provinces (such as Zhejiang, Fujian and Chongqing) by 2030. In response to such a huge MSW production, MSW incineration has been vigorously promoted as a mainstream MSW disposal method, due to its excellent performance in conserving land, reducing waste and energy regeneration (Tian et al.,

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2012; Li et al., 2015; Li et al., 2016; Zhou et al., 2018). Despite the above-mentioned advantages of MSW incineration, large amounts of air pollutants are also produced during the combustion process, which will cause serious environmental pollution and public health problems (Tian et al., 2012; Li et al., 2019; Chen et al., 2022).

To prevent the environmental and health damage caused by this large-scale, fast-growing MSW incineration, the Ministry of Ecological Environment (MEE) of China required MSW incineration plants to install automatic pollution source monitoring equipment, establish a network with environmental protection departments and publish real-time emission information to the public, especially for conventional air pollutants (i.e., PM, SO_2, NO_X, HCl and CO) (MEE, 2017a). Meanwhile, the Chinese government tightened emission standards for MSW incineration in 2014 (GB, 18485-2014; MEE, 2014) based on 2001 standards; in particular, the hourly concentration limits of conventional air pollutants were reduced by 62.5%, 61.5%, 25.0%, 20.0% and 33.3%, respectively. In addition, to reduce the pressure of MSW incineration at the source and enhance the efficiency of waste recycling, Shanghai implemented China's first local municipality regulations on waste sorting in July 2019 (SMPC, 2019; Wang et al., 2021), with MSW classified into four categories, namely recyclable waste, kitchen waste, hazardous waste and other waste, which ushers China into a new era of urban recycling (Wang et al., 2021). These measures were designed to increase the transparency of pollution emissions information and public participation in the pollution control of MSW incineration plants.

To date, research on introducing the measured data from continuous emissions monitoring systems (CEMS) into the emissions estimation method of the MSW incineration industry is still lacking. However, the real-time CEMS monitoring data has already been widely used in establishing emission inventories for the coal-power, iron and steel and cement industries (Liu et al., 2019; Tang et al., 2019, 2022; Bo et al., 2021) and has significant advantages in identifying emission characteristics, reducing estimation uncertainty and improving the spatial-temporal resolution of emission inventory. In terms of emission factor, due to the lack of CEMS-measured concentration data, the existing studies have to depend on average, invariable and outdated emission factors to approximately estimate the overall emissions (Tian et al., 2012; Zhou et al., 2018; Fu et al., 2022). This makes it difficult to accurately reflect the changes in emission levels caused by technological upgrades, standards tightening and policy implementation, and the heterogeneity of individual emissions.

In terms of regional scale, previous studies have mainly focused on the city, province and national scales. For the city scale, the emission characteristics of air pollutants from MSW incineration plants have been explored in different cities, such as Harbin (Bie et al., 2007), Yongcheng (Liu et al., 2021), Shuozhou (Zhao et al., 2012) and Shanghai (Chen et al., 2022). For the province scale, the emission inventory and spatial-temporal variation of air pollutants for various industries (including the MSW incineration industry) were explored in Shandong province (Jiang et al., 2020; Zhou et al., 2021). For the national scale, Tian et al. (2012), Li et al. (2021), Zhou et al. (2018) and Fu et al. (2022) estimated the total emissions of air pollutants in 2010, 2014, 2015 and 2017, respectively, based on the average, outdated emission factors obtained from the literature review. Therefore, this study intends to fill in the literature gap by using the latest CEMS-measured concentration data to provide nationwide, up-to-date and plant-level emission factors to reveal the emission level of Chinese MSW incineration plants as accurately as possible.

To the best of our knowledge, this study is the first attempt to develop a nationwide air pollutant emission inventory of MSW incineration plants in China based on the measured concentration and MSW incineration amount data to evaluate the effectiveness of implementing the new emission standards and estimate the future reduction potentials. Compared to existing research, this study generates the following three contributions: (1) the CMES-measured data was introduced into the emissions estimation method system of the MSW incineration industry; (2) a high temporal (daily-frequency) and spatial (plant-level) resolution emission inventory of the Chinese MSW incineration industry in 2019 at the national scale was constructed by using a bottom-up approach based on the up-to-date, actual, plant-level emission factors; and (3) the emission characteristics (standard-reaching proportion, emission factor and absolute emission) of air pollutants after the implementation of the new emission standards and future emission reduction potentials by reaching the stricter local emission standards and fully implementing waste sorting policy were systematically analyzed.

The main aims of this research were to: (1) evaluate the effectiveness of implementing the new emission standards by examining the standard-reaching proportion of air pollutants; (2) estimate air pollutant emissions of Chinese MSW incineration plants based on the up-to-date, actual, plant-level emission factors; and (3) explore the best and feasible future emission reduction options taking into account the latest promulgated MSW incineration management policies. These findings provide helpful insights into future policymaking and technology selection for China and other countries seeking targeted opportunities for reducing emissions from the MSW incineration industry.

2. Materials and methods

2.1. MSW incineration plants in China

China's CEMS monitoring network is a direct, real-time measurement framework of source-level hourly pollutants concentrations and operating parameters, such as flow rate, oxygen content and incineration temperature. Installation location, daily operation management, comparative monitoring, calibration testing, data audit processing and data transmission of the CEMS monitoring system were all conducted following relevant standards (HJ/T 76–2017, HJ/T 75–2017 and HJ/T 373–2007) to ensure the reliability and accuracy of the data. In this study, the CEMS database encompassed 993 blowdown stacks at 412 MSW incineration plants across 30 provinces and municipalities in China, excluding Hong Kong, Macao, Taiwan, Tibet and Qinghai. In 2019, 85.7% of these plants employed grate firing incinerators (GFIs) and the remaining employed fluidized bed incinerators (FBIs). The incorporated daily MSW incineration treatment capacity in this study reached 434 kilotons (kt), accounting for 94.8% of the total MSW incineration treatment capacity. Fig. 1 shows the geographic location, treatment capacity, incinerator type and MSW incineration amount of Chinese MSW incineration plants in 2019.

2.2. Emissions estimation

This study adopted a bottom-up approach to estimate the absolute emissions of Chinese MSW incineration plants. For plant-level emissions estimation, the emission factor was used to calculate the emissions of each plant, which were then aggregated to obtain city-, provincial- and regional-level emissions (Tang et al., 2019, 2020a).

The absolute emissions of each plant were estimated by multiplying the activity level by the corresponding emission factor.

$$E_{i,j} = A_{i,j} \times EF_{i,j} \quad (1)$$

where the subscripts i and j indicate the air pollutant and plant; E denotes the total pollutant emissions from the MSW incineration plant i (t); A denotes the activity level, defined as the annual MSW incineration amount per MSW plant (10^4 t), which is derived from the China Urban Construction Statistical Yearbook issued by the Ministry of Housing and Urban-Rural Development of China; and EF stands for the emission factor, defined as the mass of emitted pollutant per unit of incinerated MSW (g t^{-1}).

Generally, emission factors can be derived by field measurements, mass balance methods and literature review. The CEMS, as a real-time field measurement method, can reflect the daily or even hourly emis-

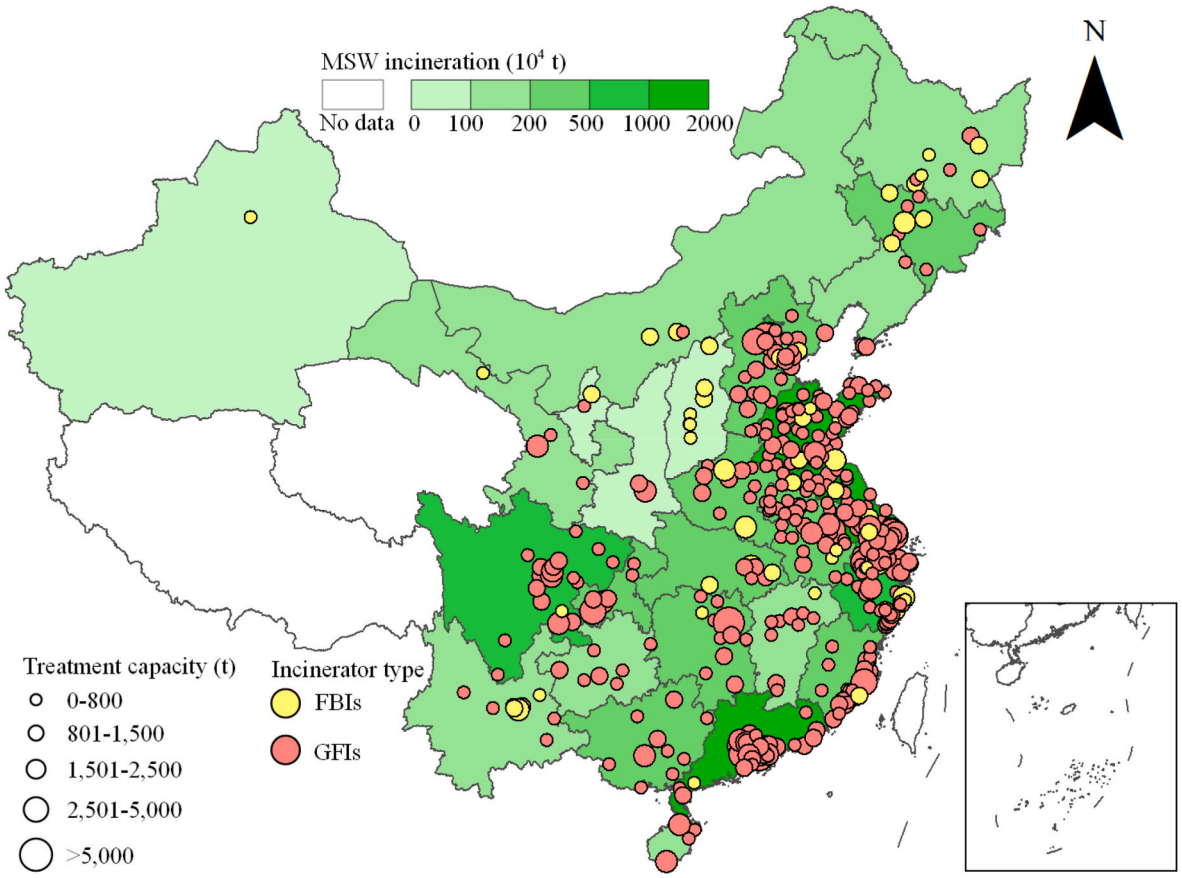


Fig. 1. Geographical distribution of MSW incineration plants in 2019.

sion levels of pollutants. Thus, the emission factors were estimated by multiplying the corresponding CEMS-measured concentration of each pollutant by the theoretical flue gas rate (Tang et al., 2019, 2022; Bo et al., 2021).

$$EF_{i,j} = C_{i,j} \times V \tag{2}$$

where C denotes the pollutant concentration in the flue gas (mg m^{-3}) measured by the CEMS network, and V denotes the theoretical flue gas rate, defined as the volume of flue gas per unit of incinerated MSW (Nm^3 t^{-1}), which is derived from the second national survey of pollution sources issued by the MEE.

2.3. Assessment of compliance with emission standards

Using CEMS-measured concentrations of PM, SO_2, NO_X, CO and HCl, the standard-reaching proportion was evaluated to reveal the effectiveness of implementing the new emission standards. The standard-reaching proportion can be defined as the proportion of observations in compliance with the associated emission standards, ranging from 0% (representing an utter noncomplier at any time) to 100% (representing a full complier over the entire sampling period) by using daily concentration data according to the following equation:

$$S_{i,j} = n_{i,j} / N_{i,j} \tag{3}$$

where $S_{i,j}$, $n_{i,j}$ and $N_{i,j}$ are the standard-reaching proportion, standard-reaching operating days and annual operating days for pollutant i in incinerator smokestack j under the corresponding emission standards, respectively.

2.4. Scenario analysis

Socioeconomic and population development processes are related to MSW generation. Predicting MSW production by province should consider the relationship between the change in MSW generation and the economic and population development levels in China's provinces. The urban population and household disposable income were adopted as explanatory variables based on previous research results (Shapiro-Bengtsen et al., 2020). Thus, the general model equation can be defined as:

$$\log\left(M_r^t\right) = \alpha_0^r + \alpha_1^r \times \log\left(I_t^r\right) + \alpha_2^r \times \log\left(P_t^r\right) + \alpha_3^r \times T_t + \delta_t^r \times D_t^r \tag{4}$$

where *log* is the natural logarithm; M denotes the MSW production in the province or municipality; I is the disposable income of urban residents in the provinces or municipalities based on the level in 2002; P is the urban population in the provinces or municipalities; T and D represent time and dummy-variables, respectively; r and t denote the region and year, respectively; and α_0^r, α_1^r, α_2^r, α_3^r and δ_t^r are the estimated coefficients. Eq. (4) can be interpreted as follows: if the household income in each region increases by 1%, the corresponding MSW production increases by α_1^r%, and if the urban population in a given region increases by 1%, the corresponding MSW production increases by α_2^r%.

In 2017, the National Development and Reform Commission issued the Notice on Further Planning and Site Selection of Municipal Waste Incineration Power Plants, requiring all provinces or municipalities to formulate medium- (2025) and long-term (2030) special plans for MSW incineration plants. Furthermore, local provinces or municipalities formulated stricter pollutant emission standards for MSW incineration than the national standard (MEE, 2014) to further control the emission of pollutants. Therefore, considering the continuous strengthening of the implementation of emission reduction and waste sorting policy, three

future scenarios were proposed targeting the MSW incineration industry in 2025, 2035 and 2050 based on MSW production prediction (Shapiro-Bengtsen et al., 2020) and future development plans of MSW incineration plants (NDRC, 2021): business-as-usual (BAU), stricter emission standards (STS) and stricter emission standards and waste sorting (STS-WS).

2.5. Uncertainty analysis

The Monte Carlo method was introduced in uncertainty analysis to verify the reliability of the estimated emissions (Shan et al., 2019; Bai et al., 2021). First, activity data, as important model input, should be considered in uncertainty analysis. Accordingly, the probability of plant-level production was assumed to obey a normal distribution with a coefficient of variation of 5% (defined as the standard deviation divided by the mean) (Zhao et al., 2011; Liu et al., 2015; Tang et al., 2019, 2020b; Bo et al., 2021). Additionally, the incinerator technology, MSW components, operating conditions and operating parameters of the individual plant may result in uncertainty when adopting a unified emission coefficient. Thus, the probability of pollutant concentrations was assumed to obey a uniform distribution corresponding to the allowed tolerance ranges based on the Technical Requirements for Installation of Online Monitoring Instruments for Flue Gas from MSW Incineration issued by the MEE (HJ 75–2017; MEE, 2017b). In this study, the Monte Carlo method was employed to generate random values of pollutant concentrations and activity levels following their respective distributions, and 10,000 simulations were conducted to estimate the uncertainty ranges of emission factors and absolute emissions in terms of two standard deviations (Chen et al., 2014; Zhao et al., 2017; Wang et al., 2019).

3. Results and discussion

3.1. Concentrations of air pollutants

As the main environmental management targets, the daily concentrations of PM, SO_2, NO_X, CO and HCl in the flue gas of Chinese MSW incinerators are illustrated in Fig. 2. The annual mean concentrations of PM, SO_2, NO_X, CO and HCl in 2019 were 5.4 ± 0.3, 18.4 ± 0.9, 136.9 ± 3.0, 11.9 ± 0.4 and 18.2 ± 1.3 mg m^{-3}, respectively. In terms of temporal changes, the concentration fluctuation ranges of the MSW incinerator were small enough to fluctuate around their mean values. The concentrations of PM, SO_2, NO_X, CO and HCl reached the lowest level around February, which may be related to the temporary shutdown of some MSW incineration plants during the Spring Festival or the implementation of emergency control policies for heavy pollution weather in Autumn and Winter (Wang et al., 2017). In addition, the regularity of the month in which the highest concentration of each pollutant occurred was not uniform. Specifically, the highest concentrations of SO_2, NO_X and HCl were observed in July or September, which may be related to changes in MSW composition (especially moisture content), as this period is in the rainy season (Dan et al., 2022). The concentrations of PM and CO reached the highest levels in April and May, which may be due to the routine maintenance for the incinerator during this period of every year with frequent start-up and shutdown of the incinerator leading to higher pollutant concentrations. The underlying reason for the influence of seasonality and MSW composition change on pollutant concentration needs to be further demonstrated by field investigation.

Furthermore, 59.8%, 62.2%, 64.4%, 70.8% and 17.8% of incinerators throughout the year met the daily concentration limits for PM (20 mg m^{-3}; red line in Fig. 2), SO_2 (80 mg m^{-3}), NO_X (250 mg m^{-3}), HCl (10 mg m^{-3}) and CO (80 mg m^{-3}), respectively. Specifically, Shanghai implemented the waste sorting policy on July 1, 2019, and the concentrations of pollutants varied greatly before and after waste sorting, whereas the concentrations of SO_2 and CO hardly changed (p = 0.73, 95% confidence interval (CI) for SO_2 = (−0.24, ∞); p = 0.26, 95% CI for CO = (−0.38, ∞); insets in Fig. 2). Meanwhile, the PM concentration decreased significantly by 4.6% ($p < 0.01$, 95% CI = (0.06, ∞)). In contrast, the concentrations of NO_X and HCl increased significantly by 6.7% and 7.7%, respectively ($p < 0.01$, 95% CI for NO_X = (-∞, −8.25); $p < 0.01$, 95% CI for HCl = (-∞, −0.17)). Xu et al. (2020) also pointed out that MSW classification changes MSW components and operating conditions of the incinerator, which may further affect the concentration of pollutants.

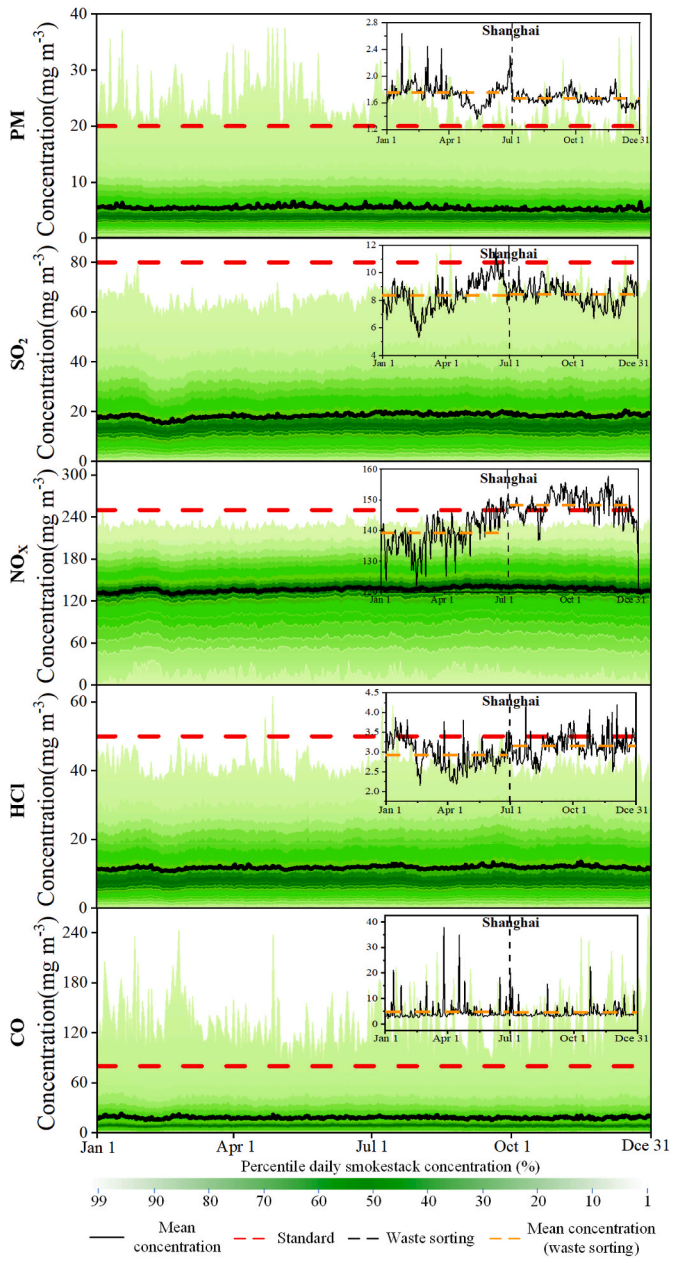


Fig. 2. Daily concentrations of air pollutants in the flue gas of Chinese MSW incinerators. The inset shows the daily concentration of air pollutants before and after the implementation of waste sorting in Shanghai's MSW incineration plants on July 1, 2019.

The daily concentrations of air pollutants in different provinces were highly spatially heterogeneous. Overall, the lowest annual mean concentration of pollutants was found in the eastern region, followed by central and southern, southwest, northern and northeast regions; the northwest region had the highest annual mean concentration. In particular, the concentrations of PM, SO_2, CO and HCl were the lowest in Shanghai due to the implementation of stricter local standards (DB 31/

768–2013; SMBEE, 2014), with means of 1.7, 9.3, 4.8 and 3.2 mg m^{-3}, respectively, which were 68.8%, 49.3%, 59.8% and 82.5% lower than the corresponding national mean concentrations. Those results also demonstrated the effectiveness of emission control regulation and the improvement of emission control technology. Furthermore, the lowest NO_X concentration was found in Beijing, with a mean value of 92.4 mg m^{-3}, which is 32.6% lower than the national mean. This is inseparable from the fact that almost all of Beijing's MSW incinerators have installed high-efficiency denitrification devices.

As with strict control of pollutant concentrations, a relatively high proportion of daily observations (measured by standard-reaching proportion) met the corresponding concentration limits of the emission standards (GB, 18485-2014) in 2019. Fig. 3 shows an overview of the standard-reaching proportions of PM, SO_2, NO_X, HCl and CO concentrations under GB 18485-2014, with means of 98.8%, 99.3%, 99.4%, 99.4% and 97.6%. This result indicates that future emission control policies, especially for CO emissions, need to be further strengthened. From the perspective of spatial level, in economically developed and densely populated areas, such as eastern and central and southern China, the standard-reaching proportions of PM, SO_2, NO_X, HCl and CO concentrations under GB 18485-2014 had the highest in China, with means of 99.4%, 99.6%, 99.5%, 99.6% and 98.2%, respectively. Conversely, in the northwestern region with a less developed economy and low population density, the standard-reaching proportion of

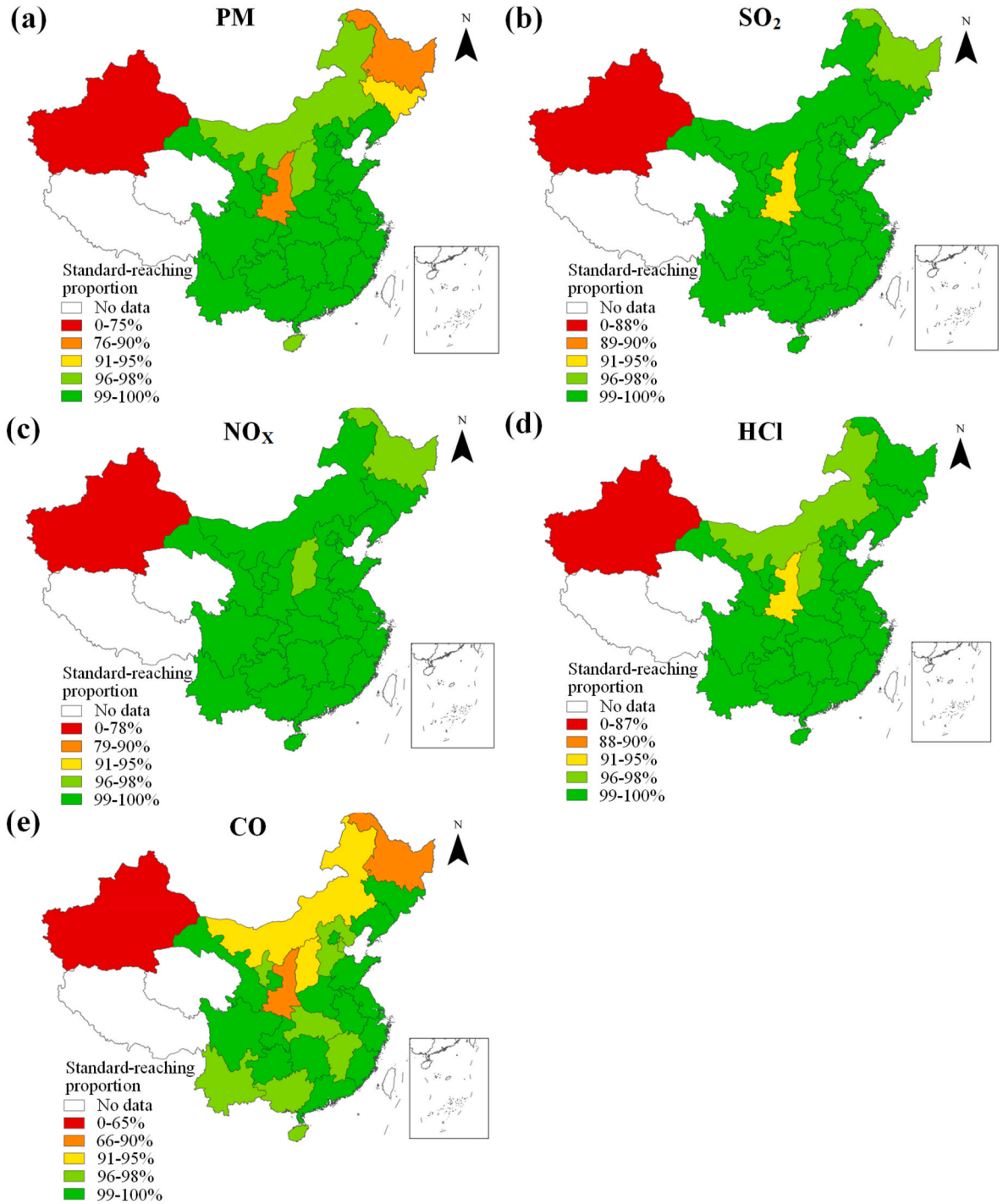


Fig. 3. The standard-reaching proportions of PM (**a**), SO_2 (**b**), NO_X (**c**), HCl (**d**) and CO (**e**) concentrations under the national emission standards in 2019.

pollutant concentration had the lowest (<97.1%). This finding suggests that policy preferences should be adjusted at the right time to achieve full compliance with emission standards by introducing advanced pollution control equipment, improving operation conditions and production processes and promoting technological innovation.

From the perspective of incinerator technology, the standard-reaching proportions of PM, SO_2, NO_X, HCl and CO concentrations under GB 18485-2014 for GFIs were higher than those of FBIs, reaching 99.0%, 99.4%, 99.6%, 99.6% and 98.1%, respectively. Furthermore, the GFI may be adapted to the high moisture content of MSW in China, which can ensure the complete combustion of MSW and further improve the incineration temperature enough to decompose pollutants (Wei et al., 2022). Therefore, the application and upgrading of GFIs should be further promoted nationwide, which has also been recommended by the Policy on Treatment of Municipal Solid Waste and Pollution Prevention and Control issued by the MHURD.

3.2. Emission factors of air pollutants

With the continuous tightening of emission standards, the emission factors for Chinese MSW incineration plants were suitably controlled, with annual means of 20.7 ± 18.1, 72.9 ± 43.9, 504.7 ± 148.4, 44.9 ± 68.6 and 67.6 ± 31.1 g t^{-1} for PM, SO_2, NO_X, HCl and CO, respectively, as of 2019. Overall, the emission factors of air pollutants were significantly lower than those in previous studies, as shown in Fig. 4a. Specifically, the emission factors in this study were 11.1–48.5%, 14.2–81.0%, 44.7–79.5%, 31.1–162.1% and 21.0–29.6% that of previous emission factors (Tian et al., 2012; Zhou et al., 2018; Fu et al., 2022). This decline is mainly due to the tightening of pollutant emission limits and strengthening of management and control policies in recent years, which have reversed the pressure transmission of incineration facilities to optimize operation conditions, select environment-friendly incinerator technologies and upgrade flue gas purification devices (Wei et al., 2022). The comparison results between different incinerator technologies also indicated that our emission factors were lower than or close to those reported in existing studies. More detailed comparisons between emission factors at the same level are shown in Table S1. In addition, compared to developed countries or regions (US EPA, 1996; EEA, 2006, 2007, 2009, 2013, 2016 and 2019; Beylot et al., 2018), the emission factors in China were lower than those of developed countries or regions (such as the United States and European Union) before 2009, but were higher than those of developed countries or regions (such as the European Union and France) after 2012, especially for PM, CO and HCl (Fig. 4b), which emphasizes that the Chinese MSW incineration industry still needs to further improve the efficiency of end-of-pipe pollution controls.

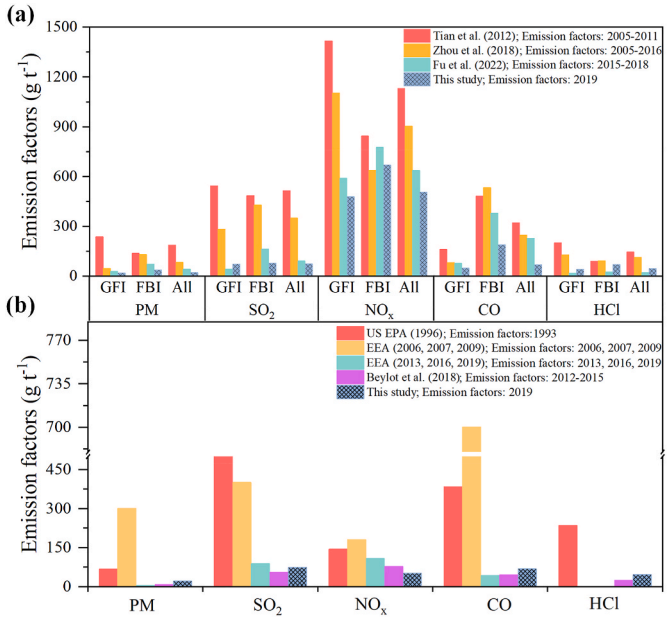


Fig. 4. Comparisons of emission factors with existing studies.

The emission factor holds a similar distribution pattern with the standard-reaching proportion in terms of spatial level and incinerator technology. In terms of spatial level, the emission factors of air pollutants were relatively lowest in the eastern and central and southern regions, while the highest in the northwest region, as shown in Fig. 5. Specifically, the annual emission factors of Shanghai's MSW incineration plants were the lowest level in China, reaching 5.9, 32.6, 496.3, 11.1 and 16.7 g t^{-1} for PM, SO_2, NO_X, HCl and CO, respectively, which is inseparable from the widespread installation of advanced air pollution control devices (APCDs), including selective non-catalytic reduction (SNCR), selective catalytic reduction (SCR) devices, wet and semi-dry scrubbers and/or dry scrubbers and activated carbon injection coupled with bag filters. In terms of incinerator technology, the emission factors of GFIs with means of 18.1, 72.1, 477.3, 40.8 and 47.1 g t^{-1} for PM, SO_2, NO_X, HCl and CO, were 50.1%, 6.8%, 28.6%, 41.2% and 75.0% lower than those of FBIs, respectively. This may be attributable to the limitations of FBIs treatment technology, such as the high moisture and low calorific value of MSW, and the addition of coal to promote stable combustion resulting in higher pollutant emission factors (Zhao et al., 2016; Fu et al., 2022).

3.3. Emissions estimation in 2019

To provide a clear understanding, the emissions estimation results were analyzed in terms of pollutant species, spatial levels and air pollution control devices. Overall, the emissions of PM, SO_2, NO_X, HCl and CO were estimated at approximately 1.9, 6.2, 50.8, 4.3 and 6.6 kt yr^{-1}, respectively. Our results show that NO_X was at the top of the pollutant emissions, which is consistent with previous studies (Tian et al., 2012; Chen et al., 2022; Fu et al., 2022). NO_X emissions have been widely identified as a determinant of acid rain, stratospheric ozone reduction and photochemical smog (Bo et al., 2019). Regarding NO_X removal, the SNCR denitrification equipment widely used in the waste incineration industry can reduce the NO_X emission coefficient by approximately 50–75% (Chen et al., 2022).

Generally, the stability of flue gas purification equipment can be affected by multiple factors, including MSW composition, fluctuations in moisture content and calorific value and corrosion of flue gases. Specifically, the performance of the SNCR process may be affected by the temperature, mixing conditions, the ratio of reagent to NO_X and NO_X concentration in the flue gas (Chen et al., 2022). Hu et al. (2019) also found that SNCR injection location and ratio could significantly improve NO_X removal efficiency. Consequently, it is further recommended to implement combined SNCR and SCR denitrification equipment or switch to SCR denitrification equipment (as one of the feasible technologies required by the Technical Specification for Application and Issuance of Pollutant Permit-Municipal Solid Waste Incineration (HJ 1039–2019; MEE, 2019)), which may result in a reduction of approximately 50–95% or 80–95%, respectively, in the NO_X emission factor (Chen et al., 2022).

The emissions of PM, SO_2, NO_X, HCl and CO in the spatial distribution pattern exhibited high heterogeneity, as shown in Fig. 6. The total emissions of air pollutants at the provincial level were significantly positively correlated with the number of incinerators ($r = 0.83$, $p < 0.01$) and MSW incineration amount ($r = 0.98$, $p < 0.01$). The majority (72.6%) of MSW incineration plants are mainly concentrated in the eastern and central and southern regions with a large population and developed economies (Zheng et al., 2014). These regions, with the highest proportion of MSW production (62.1%) and MSW incineration amount (69.8%), produced the highest share of total emissions, contributing 64.9%, 61.9%, 67.4%, 67.0% and 62.2% for PM, SO_2, NO_X, HCl and CO, respectively. From a provincial perspective, Guangdong,

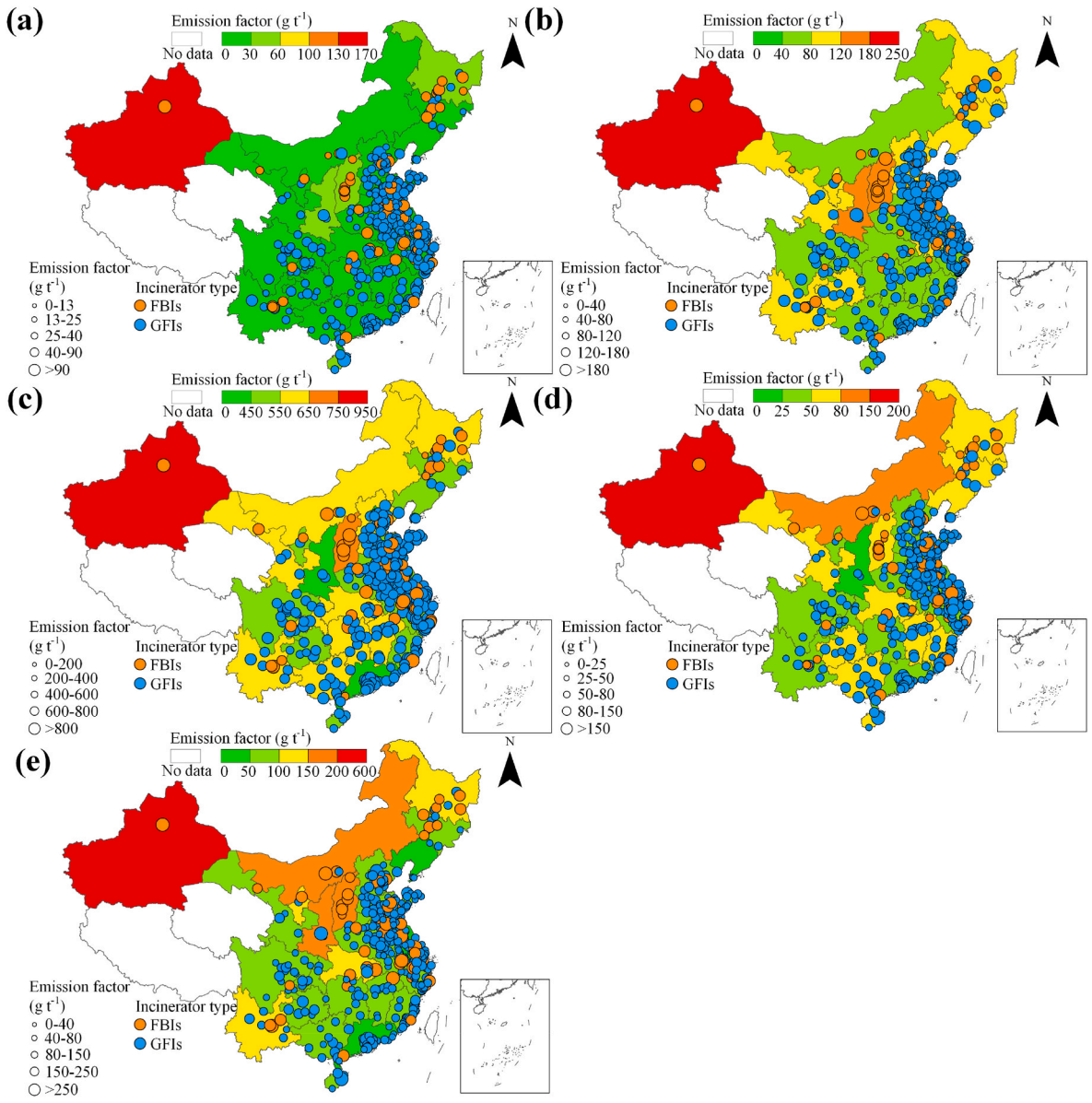


Fig. 5. Emission factors of PM (**a**), SO_2 (**b**), NO_X (**c**), HCl (**d**) and CO (**e**) in 2019.

Shandong and Jiangsu were the top three contributors to PM, SO_2, NO_X, HCl and CO emissions. This is mainly because the proportion of MSW incineration amount in each province largely determines the corresponding air pollutant emission level (refer to Eq. (1)). Accordingly, the pollutant emissions were highly consistent with the spatial distribution of the MSW incineration amount, whose Pearson correlation coefficients with PM, SO_2, NO_X, HCl and CO emissions reached 0.9, 0.9, 1.0, 0.9 and 0.8, respectively.

In addition, the application rate of air pollution control devices across provinces will also affect the emission level of air pollutants. For example, almost all MSW incineration plants in Beijing contain installed denitrification devices; approximately 70.0% of plants have been equipped with high-efficiency SCR and SNCR combined devices, and the remaining plants have deployed SNCR or SCR devices. Accordingly, the NO_X emission factor of MSW incineration plants in Beijing was 323 g t^{-1}, which is the lowest in the country and 44.6% lower emissions than those in Tianjin and Hebei with the same total incineration scales. Similarly, Shanghai exhibited the highest installation rate of deacidification and dust removal devices, with approximately 71.6%, 100% and 100% of plants employing wet flue gas desulfurization, dry/semi-dry flue gas desulfurization and bag-type strainer devices, respectively. This directly led to the lowest PM, SO_2 and HCl emission factors for Shanghai's MSW incineration plants in China, with emissions 35.3%, 71.0%, and 76.0% lower, respectively, than those in provinces with the same total incineration scales, such as Hebei and Gansu.

Fig. S1 shows a comparison of the air pollutant emissions determined in this study to those reported in existing studies. Although China's MSW incineration amount continued to grow at a rate of 24.5% per year from 2010 to 2019, our estimates were 22.2–75.8% lower than previous results obtained for PM, SO_2 and CO, highlighting a notable mitigation effect in recent years, largely because the reduction rate of emission factors was greater than the growth rate of MSW incineration amount. However, NO_X and HCl emissions increased by 78.4% and 18.1%, respectively, from 2010 to 2019, indicating that growth in MSW incineration amount may be the main driving factor of the growth in the emission of these pollutants.

Facing the potential pressure of future emission mitigation, especially for NO_X, some provinces and municipalities, such as Shanghai, Tianjin, Hebei, Fujian, Shandong, Hainan and Shenzhen, have introduced more stringent emission targets with daily mean NO_X

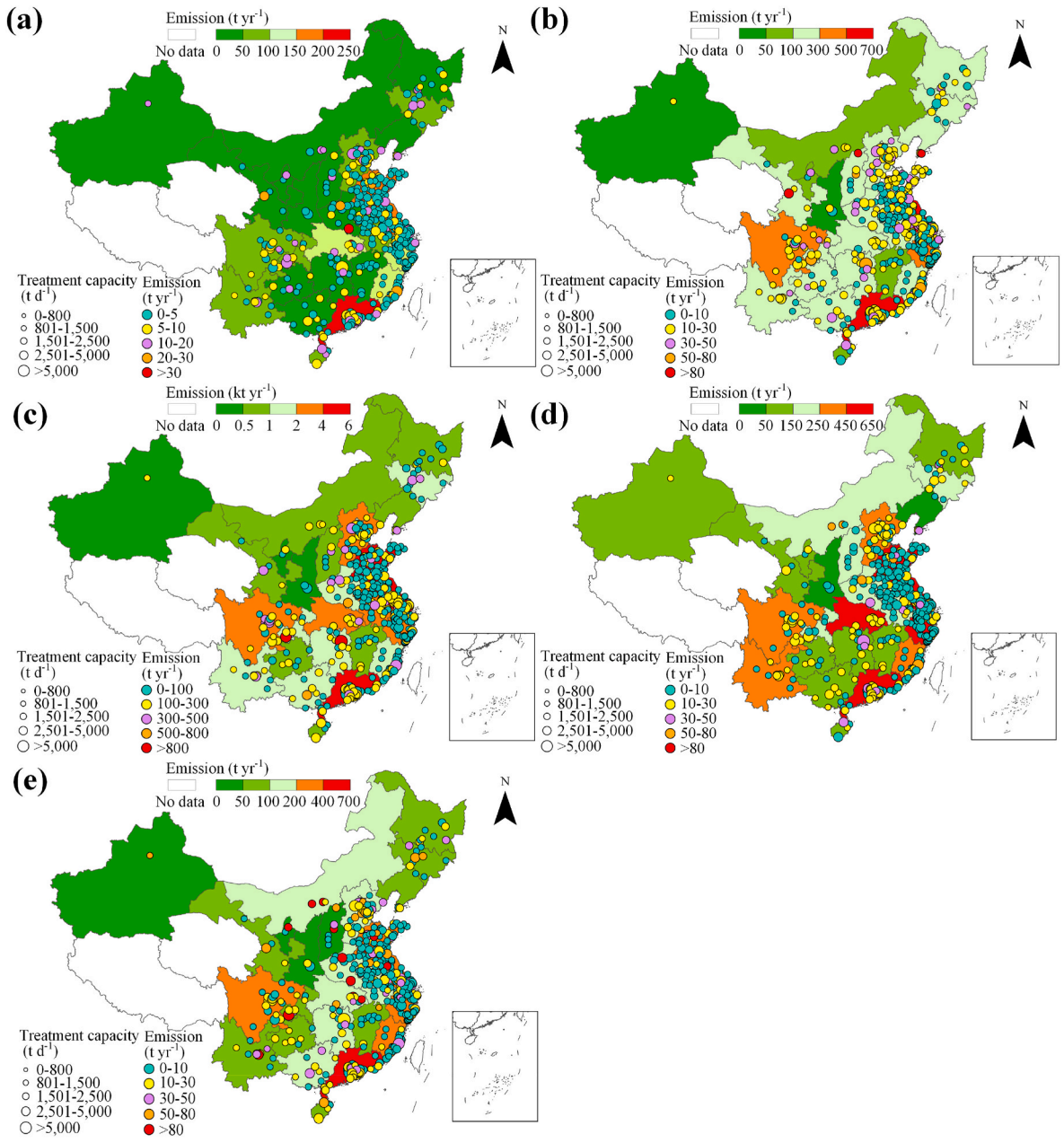


Fig. 6. Emissions of PM (**a**), SO_2 (**b**), NO_X (**c**), HCl (**d**) and CO (**e**) in 2019.

concentrations of 200, 150, 120, 120, 120, 120 and 80 mg m^{-3}, respectively, which is 20–68% lower than the current national standard limits (250 mg m^{-3}). Table 1 summarizes the latest air pollutant emission standards for the MSW incineration industry. Therefore, to meet more stringent NO_X emission limit, SCR devices should continue to be deployed on the basis of SNCR denitrification devices, which could reduce the pollutant concentration and emission factor to <100 mg m^{-3} and 220–550 g t^{-1}, respectively (Chen et al., 2022).

3.4. Influencing factors of MSW production

The socioeconomic development level and regional population scale are related to MSW generation (Andersen and Larsen, 2012; Shapiro-Bengtsen et al., 2020). Therefore, MSW generation modeling requires an analysis of the links between changes in waste generation and economic and demographic development levels in provinces or municipalities. Fig. S2 shows the influencing factors of MSW production by province or municipality in China. MSW production in each province or municipality was highly correlated with the urban population scale and regional economic development level ($r = 0.94$, $p < 0.01$ and $r = 0.96$, $p < 0.01$, respectively), which is highly consistent with existing research (Andersen and Larsen, 2012; Wei et al., 2013; Jaligot and Chenal, 2018; Shapiro-Bengtsen et al., 2020). However, the correlation between the other variables and MSW production was low ($r < 0.50$) and not significant ($p < 0.10$). Based on the correlation between the population scale, regional economic development level and MSW production, the latest management policies in the MSW incineration industry were considered to predict its MSW incineration amount in each province or municipality in 2025, 2030 and 2050. Moreover, the emission factors and absolute emissions of air pollutants were evaluated by continuously tightening emission standards implemented by the province or municipality.

This study analyzed the temporal variation of future MSW production proposed by Shapiro-Bengtsen et al. (2020) under the different

Table 1
Comparison of concentration limits of MSW incineration in representative countries or regions (unit: mg m^{-3}).

Country or Region	PM	SO_2	NO_X	CO	HCl
China (GB, 18485-2014; MEE, 2014)	20	80	250	80	50
Hebei, China (DB 13/5325-2021; DEEHP, 2021)	8	20	120	80	10
Tianjin, China (DB 12/1101–2021; TEEB, 2021)	10	40	150	100	20
Shanghai, China (DB 31/768–2013; SMBEE, 2014)	10	50	200	50	10
Fujian, China (DB 35/1976–2021; FPDEE, 2021)	–	–	120	–	–
Shenzhen, China (SZDB/Z 233–2017; SAMR, 2017)	8	30	80	30	8
Hainan, China (DB 46/484–2019; DEEHP, 2019)	8	20	120	30	8
Shandong, China (DEESP, 2021)	8	30	120	80	10
EU (European Union, 2010)	10	50	200/400[a]	50	10
U.S.[b] (US EPA, 1995; 2006)					
Existing & Large-scale incinerator	19.1	60	270	89	32.5
Existing & Small-scale incinerator	53.5	162.6	–	89	280
New & Large-scale incinerator	15.3	61	219	89	28
New & Small-scale incinerator	18.3	61	–	89	28
Japan (Japan MOE, 2006)					
Relatively large-scale incinerator [c]	44.4	–	522.6	38.2	777.7
South Korea (Seo, 2013)	20	78.5	131.7	57.3	29.9

Notes: [a] Existing incinerators of less than 6 Mg h^{-1}; [b] In the U.S., large scale refers to larger than 225 Mg d^{-1}, while small scale refers to larger than 35 Mg d^{-1}; [c] In Japan, relatively large scale refers to larger than 4 Mg h^{-1} or discharging more than 40,000 Nm^3 h^{-1} of flue gas.

scenarios (Fig. 7). Compared to 2019, MSW production under the BAU/STS scenario revealed a trend of continuous growth (7.4–40.7%), whereas this trend gradually decreased (22.4–29.2%) under the STS-WS scenario owing to the contribution of waste sorting from 2025 to 2050. Specifically, MSW production was predicted to reach 341 and 172 million tons in 2050 under the BAU/STS and STS-WS scenarios, respectively. The temporal variation of MSW production in China was closely related to the regional economic development level and population scale. Under the BAU/STS scenario, MSW production in the developed regions along the eastern coast was predicted to grow rapidly from 2025 to 2050, such as in Zhejiang (with a growth ranging from 42.6 to 160.7%), Fujian (20.0–111.4%) and Tianjin (36.1–95.9%). Furthermore, if the MSW sorting policy is fully implemented in densely populated areas, such as Beijing, Guangdong and Shanghai, MSW production in 2050 will decrease by 51.9–54.6%, 32.2–39.9% and 31.5–34.5%, respectively, compared with that in 2019.

3.5. Estimation of future emissions

The implementation of more scientific MSW management policies and the application of more effective flue gas purification systems can generate a positive impact on future emission mitigation of MSW incineration, despite the continuous and rapid growth in MSW incineration amount. The total emissions were estimated under the three future scenarios (BAU, STS and STS-WS) according to the planned incineration proportion, projected MSW production and upcoming emission standards. The total emissions by province or municipality under the different scenarios are illustrated in Fig. S3. Under the BAU scenario (Fig. S3(a)), the total emissions of PM, SO_2, NO_X, CO and HCl were expected to increase by 129.6–294.3%, 127.9–287.2%, 95.1–232.9%, 114.6–265.5% and 116.2–266.9%, respectively, in 2025, 2030 and 2050, based on the assumption that the emission factors of each pollutant remain unchanged from those in 2019. This result suggests that the pollutant emissions from 2025 to 2050 will mainly be driven by MSW incineration amount. In terms of spatial level, Zhejiang, Guangdong and Jiangsu were still the main emission hotspots in the future, accounting for 27.4%, 28.3% and 32.1%, respectively, of total emissions in 2025, 2035 and 2050. This finding suggests that effective penalties, incentives and policy preferences should be separately implemented due to the heterogeneity in regional emissions.

With the continuous tightening of emission standards issued by local governments, the application of more efficient flue gas purification equipment in the future could further reduce emissions. Under the STS scenario (Fig. S3(b)), it was assumed that emission standards were continuously tightened to the strictest existing standards. The absolute emissions of PM, SO_2, NO_X, CO and HCl in 2025, 2030 and 2050 were predicted to be reduced by 7.5–30.1%, 1.1–28.8%, 2.3–42.8%, 3.8–34.9% and 2.9–46.7%, respectively, compared to BAU scenario levels. This may require further promotion of the application of a highly efficient flue gas purification system, with SCR and SNCR devices for denitrification, wet flue gas desulfurization for SO_2 and HCl removal, and cyclone and bag dust filters for PM removal. Compared to the BAU scenario, emission hotspot regions, such as Zhejiang, Guangdong and Jiangsu, will have the largest emission reductions of PM, SO_2, NO_X, CO and HCl in 2050, decreasing by 21.9–24.3%, 20.2–24.5%, 33.6–43.6%, 28.5–41.5% and 38.7–44.3%, respectively. These findings highlight the substantial benefits of strengthening emission standards and outline the prospects for a sustainable management strategy.

The pollutant emissions after the implementation of waste sorting combined with the increasingly stringent emission standards were estimated to analyze the mitigation effect of policy implementation (Shapiro-Bengtsen et al., 2020). Specifically, the implementation of the waste sorting policy will be conducive to improving the recycling rate and reducing the amount of waste incineration (Liu et al., 2017; Tong et al., 2020). In 2019, the dry waste incinerated amount after the implementation of waste sorting in Shanghai decreased by 26.0% from 2018 levels, while the recyclable waste and wet waste amounts increased by 5 and 1.3 times, respectively (Tong et al., 2020; Fu et al., 2022). Under the STS-WS scenario (Fig. S3(c)), if the waste sorting policy is gradually implemented nationwide, the total MSW incineration amount in 2025, 2030, and 2050 will be reduced by 27.7%, 35.7%, and 49.7%, respectively, resulting in total PM, SO_2, NO_X, HCl and CO emissions reductions of 32.3–64.2%, 25.8–61.8%, 28.8–70.9%, 27.7–65.2% and 28.8–72.7%, respectively, from BAU scenario levels. Furthermore, Zhejiang, Guangdong and Jiangsu, as high-emission regions, will reduce total emissions by 46.5–73.5%, 46.2–73.1%, 46.4–78.7%, 47.3–77.3% and 46.9–79.3%, respectively, which exceed the corresponding national mean reductions in pollutants by 12.0%, 16.7%, 14.7%, 16.4% and 21.7%, respectively. Therefore, our results indicate that the implementation of the waste sorting policy can not only reduce the amount of waste incineration but also achieve the goal of emission reduction.

The continuous tightening of emission standards from 2025 to 2050 could lead to a continuous reduction in emission factors. Fig. S4 shows the emission factors for MSW incineration by province or municipality in 2025, 2030 and 2050. Overall, the emission factors tended to be the lowest in 2050, with annual means of 17.8 ± 6.6, 52.0 ± 14.9, 295.7 ± 27.8, 26.1 ± 5.2 and 58.8 ± 29.9 g t^{-1} for PM, SO_2, NO_X, HCl and CO, respectively, which are 37.2%, 31.9%, 44.9%, 39.3% and 52.2% lower than those in 2019. Compared to coal-fired power plants retrofitted with ultra-low emissions (ULE) technology (with annual means of 30, 170 and 410 g t^{-1} for PM, SO_2 and NO_X in 2017, respectively) (Liu et al., 2019), the pollutant emission factors of MSW incineration plants in the future will be below this ultra-low level. This suggests that the administrative means of tightening emission standards can effectively reduce the emission factors of MSW incineration plants to below the ULE level of thermal power plants.

From the spatial perspective, the NO_X emission factor of MSW incineration plants in Beijing will be expected to reach the lowest level (241 g t^{-1}) in China in 2050. However, the emission factors of the remaining four pollutants will be lowest in Shanghai, with annual means

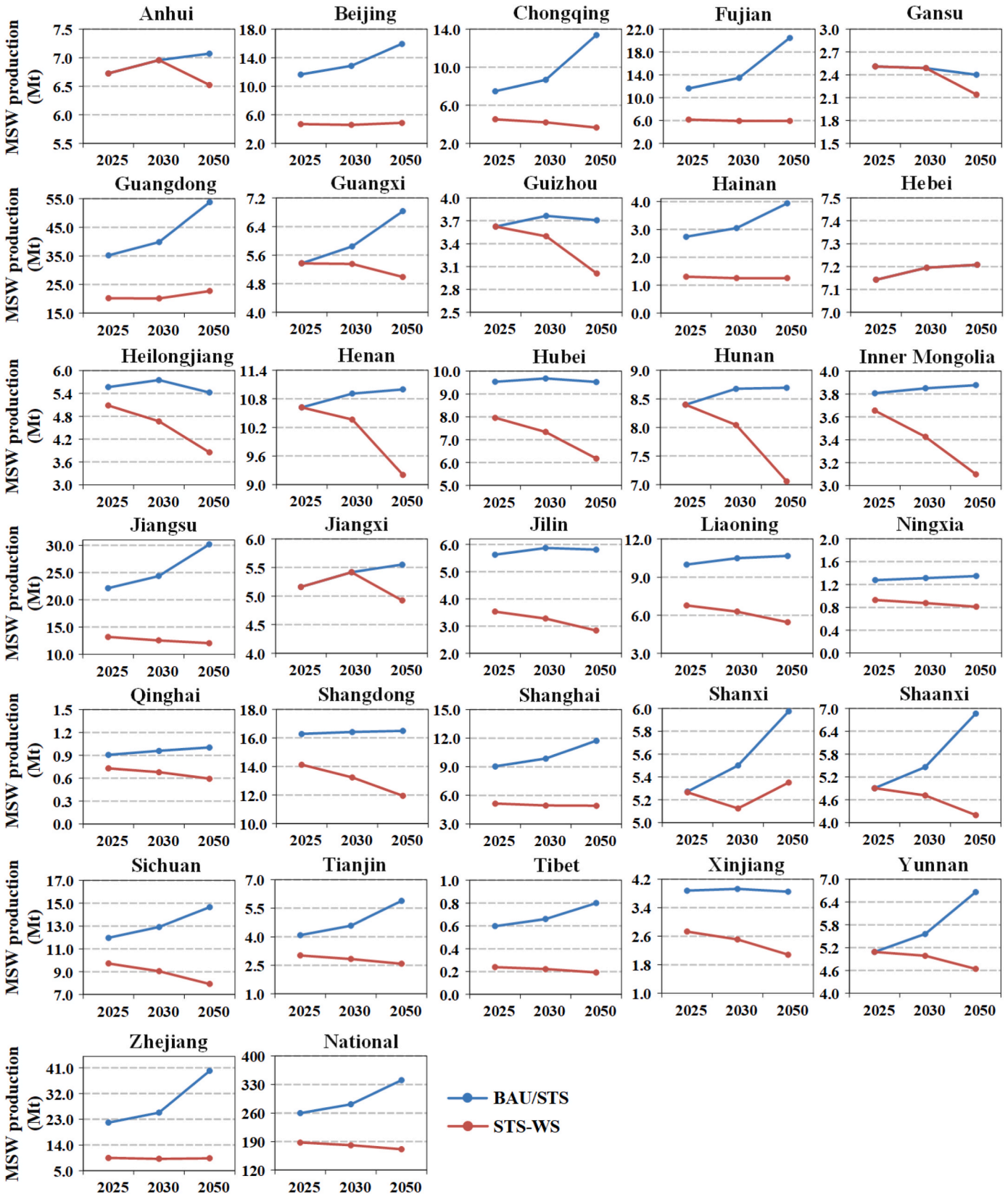


Fig. 7. Projected MSW production by province or municipality in 2025, 2030 and 2050 (BAU (business-as-usual), STS (stricter emission standards), STS-WS (stricter emission standards and waste sorting)).

of 5.4, 24.7, 8.9 and 12.8 g t^{-1} for PM, SO_2, HCl and CO, respectively. Compared with 2019, the emission factors of MSW incineration plants in Xinjiang province in 2050 will have the largest reduction potential in China, with the reduction rate of 77.9%, 60.3%, 59.8%, 81.2% and 76.4% for PM, SO_2, NO_X, HCl and CO, respectively. From the pollutant perspective, the decrease rates of the NO_X and HCl emission factors in each province were the largest compared with other pollutants, indicating that the inhibition effects of strengthening emission standards on NO_X and HCl were significantly higher than that on other pollutants.

3.6. Uncertainty analysis

The Monte Carlo method was used to analyze the uncertainty in the emission inventory for the MSW incineration industry. According to the probability distributions of the input parameters (such as the pollutant concentration and activity level), the input parameters were randomly and repeatedly sampled, and corresponding emission factor and emission distributions under the different parameter values were obtained to quantify the error in the emission inventory. A total of 10,000 Monte Carlo simulations were conducted considering the 95% confidence interval to estimate the uncertainty ranges of the emission factors and absolute emissions. The uncertainty ranges of the estimated emission factors and absolute emissions were ±1.0% and ±1.4%, respectively, for PM; ±0.7% and ±1.1%, respectively, for SO_2; ±0.6% and ±1.1%, respectively, for NO_X; ±0.8% and ±1.3%, respectively, for CO; and ±0.7% and ±1.1%, respectively, for HCl, indicating that emissions estimation based on real-time CEMS measurements was relatively stable.

4. Conclusions

This study developed the first nationwide air pollutant emission inventory of MSW incineration plants in China based on the measured concentration and MSW incineration amount data to evaluate the effectiveness of implementing the new emission standards and estimate the future reduction potentials. The overall standard-reaching proportion of air pollutant concentrations has reached more than 97.6% under the national emission standards (GB, 18485-2014). The total emissions of air pollutants in 2019 decreased by 33.6–75.8% compared with those in 2015, mainly due to the sharp decrease in emission factors. Emission hotspots were mainly concentrated in eastern and central and southern regions. The future scenario of implementing waste sorting and tightening emission standards may be the preferred solution for future emission mitigation, as the total emissions and emission factors will be reduced by 25.8–72.7% and 59.8–81.2%, respectively, compared with 2019. These findings may provide helpful insights into future policy-making and technology selection for China and other countries seeking targeted opportunities for reducing emissions from MSW incineration.

Future work will further evaluate the environmental impact of MSW incineration throughout the life cycle and explore the applicable management policies to maximize the benefits of MSW incineration power generation. Furthermore, the air quality model and health risk assessment model will be introduced into the method system to evaluate the health impacts of air pollutants from MSW incineration.

Author statement

Ling Tang: Conceptualization, Methodology, Writing-Reviewing and Editing. **Jing Guo:** Formal analysis, Writing-Original draft preparation, Writing-Reviewing and Editing. **Ruxing Wan**: Data curation, Visualization. **Min Jia:** Software, Validation. **Jiabao Qu:** Data curation, Formal analysis. **Ling Li**: Supervision, Writing-Reviewing and Editing. **Xin Bo**: Conceptualization, Methodology, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.121021.

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