Health effects of future dioxins emission mitigation from Chinese municipal solid waste incinerators

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Abstract: Dioxins (including 2,3,7,8-tetrachlorodibenzo-*p*-dioxin, as Group 1 Carcinogen) in the atmosphere mainly originate from incomplete combustion during municipal solid waste (MSW) incineration. To significantly reduce dioxins emission from the MSW incineration industry, China has promulgated a set of ambitious plans regulating MSW-related pollution; however, the emission reduction potentials and concomitant environmental and health impacts associated with the implementation of these programs on a national scale remain unknown. Here, we use real measurements from official environmental impact assessment systems and continuous emissions monitoring systems (covering 96.6% of national MSW incinerators) to estimate unit-level dioxins emission and concomitant environmental and health impacts. We find that in 2018, 99.3% and 66.7% of Chinese incinerators met such concentration and temperature standards, respectively, controlling the total emissions to 19.6 g toxic equivalency quantity and maintaining carcinogenic and noncarcinogenic risks significantly below safety levels nationwide. Fully achieving both current standards and future regulations will reduce emissions and health risks by 67.7% and 62.6%, respectively, with waste sorting program contributing the majority. This study reveals substantial benefits from curbing MSW-related dioxins pollution and underscores the promise of ongoing management.

Keywords: Waste incineration; Dioxins emission; Waste sorting; Air quality model; Health risk assessment

1. Introduction

Dioxins, namely polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans, are highly toxic and persistent pollutants (Wang et al., 2019), of which 2,3,7,8-tetrachlorodibenzo-*p*-dioxin ranks at the top and was listed as a Group 1 Carcinogen by the International Agency for Research on Cancer in 1997 (Kogevinas et al., 2001). Human exposure to dioxins predominantly occurs via air inhalation (Zhou et al., 2018), which substantially increases the health risks and may even cause chronic disorders such as developmental deficits, immunotoxicity, reproductive impairment and endocrine disruption (Kogevinas et al., 2001). Almost all (95%) dioxins in the atmosphere are derived from the incomplete combustion of municipal solid waste (MSW) (McKay et al., 2001), which poses a high health risk even beyond the acceptable limits defined by the US Environmental Protection Agency in many parts of the world (such as the US (VoPham et al., 2022) and India (Kumari et al., 2019)). China surpassed the US as the largest waste producer in 2004 (Zhang et al., 2010) and thereafter experienced a fast increase in MSW production (by 2.8% per year from 2004 to 2018 (CSP, 2020) versus 0.3% globally (OECD, 2021)). Over the same period, MSW incineration, boasting the merits of land saving and energy regeneration (Zhou et al., 2018; Sun et al., 2008; MHURDC, 2020), increasingly prevailed in China and grew from 5 million tonnes in 2004 (accounting for only 3% of the global MSW production) to 102 million tonnes in 2018 (45%), at an average annual growth rate of 25.0% (CPS, 2020). This growth rate was not only higher than that of other MSW disposal methods in China (3.9% and -0.6% for landfilling and composting, respectively (MHURDC, 2020)) but also higher than that of MSW incineration in many other countries or regions, such as the EU (-6.73%) (Eurostat, 2018; Eurostat, 2022) and US (0.66%) (Eurostat, 2018; Eurostat, 2022).

To prevent health damage due to this large-scale, fast-growing MSW incineration, in 2014, China reduced this limit to the strictest level globally with the policy deadline of 2016 (0.1 ng TEQ m^{-3}; GB18485-2014; Supplementary Table 1) (CEP, 2014). Furthermore, China implemented a 50% stricter local standard (0.05 ng TEQ m^{-3}) in Shenzhen (SAMR, 2017) and Hainan (HMSA, 2019) in 2017 and 2019, respectively, which exceeds the standards implemented in the EU by 50% (Lu et al., 2017), the US by 75-98% (Lu et al., 2017) and Japan by 50-99% (MEGJ, 1999). Furthermore, China has promulgated a series of even more ambitious plans to regulate MSW incineration-related emissions, involving promising programs of MSW sorting (MEEC, 2017), technology upgrading (MHURDC, 2016), operation improvement (MHURDC, 2017) and concentration standard tightening (SAMR, 2017; HMSA, 2019). However, *ex post* evaluation of whether and how Chinese MSW incinerators have complied with the new standards enforced in 2016 and *ex ante* assessment of the impact of future control plans on the environment and public health remain unknown due to a lack of actual official monitoring data regarding the corresponding policy targets—the unit-level emissions concentration and incinerator temperature nationwide.

In recent years, the dioxins emission in the MSW incineration process have received wide attention throughout the world. Dioxins emission from MSW incineration in some developed countries or regions, and even globally, have been calculated and reported. Relvas et al. (2013) reported the latest estimates of atmospheric dioxins emission from 27 emission source types in Portugal for the period 2004-2009. Saral et al. (2014) proposed a standardized toolkit developed by UNEP Chemicals to estimate Turkey's dioxins emission inventory. Song et al. (2023) used the empirical regression model of dioxins emission to establish emission inventories of 17 toxic PCDD/Fs congeners from 8 industries worldwide during 2002-2018. In China, Tian et al. (2012), Zhou et al. (2018) and Li et al., (2021) collected the average, uniform emissions factors based on the literature review and further combined them with the total amount of MSW incineration to calculate dioxins emission from Chinese MSW incineration power plants for 2010, 2015 and 2017, respectively. However, these average emissions factors do not entail real measurements but are proxies for typical techniques, which might result in high uncertainty. In the meantime, the emissions factors used in existing inventories are invariable at the national level, thereby failing to reflect individual heterogeneities.

To improve the transparency of MSW incineration pollution emissions, the Chinese government has required national MSW incineration power plants to disclose their pollution emission data since 2020, which provides the possibility to truly reflect the level of dioxins emission from MSW incineration power plants in China. Fu et al. (2022) and Wei et al. (2022) compiled a national inventory of dioxins emission by collecting concentration data from provinces and cities across the country. However, although these studies have evaluated the latest levels of dioxins emission from MSW incineration power plants in China, they did not explore the environmental and health impacts caused by dioxins emission under existing standards policies, nor did they comprehensively analyze the extent of emission reduction potential brought by the implementation of future industry development plans. Consequently, policymakers have not been clearly informed of the actual, detailed effects of existing policies and the substantial benefits of fully implementing future control regulations.

Furthermore, existing studies have explored the influence of unit information (including control technology, incineration technology, auxiliary fuel, waste composition, and incineration temperature) on dioxins emission levels. Cheng and Hu. (2010a) believed that control technology and incinerator type directly affect whether dioxins emission concentration is up to the standard, and proposed that the installation of bag dust removal and activated carbon injection devices can effectively achieve the dioxins emission concentration of 0.1 ng TEQ m^{-3}, and also found that the distribution patterns of dioxins homologous compounds under different furnace type technologies were very different. Chen et al. (2008) and Lin et al. (2015) found that adding auxiliary fuel (such as coal) to the incinerator can effectively inhibit the synthesis of dioxins, resulting in a lower dioxins emission factor than that without adding auxiliary fuel. Wei et al. (2022) discussed the influence of control technology, operating conditions, incineration quantity, treatment capacity, incinerator type and operating years on the level of dioxins emission. It is pointed out that the control technology of semi-dry scrubber, activated carbon injection and fabric filter (SDS+ACI+FF) can remove 97.3-99.4% of dioxins in the flue gas. And it was found that the dioxins emission during the start-up and shutdown period were higher than under normal operating conditions. Grate firing incinerator, a widely used incinerator type technology, has a much lower emission factor compared to fluidized bed incinerators, and regions with high daily treatment capacity, long operating years, and high MSW incineration scale have correspondingly higher levels of dioxins emission. Therefore, the introduction of unit information provides a basis for demonstrating the effectiveness of policy implementation at the micro-dimension level.

Here, we introduce actual official monitoring data retrieved from China's national EIA system and CEMS to develop a new dataset for Chinese MSW incineration power plants (Fig. 1), denoted as the Chinese Emissions Accounts for MSW Incineration (CEAWI). Specifically, we combine and analyze the following two types of data: real measurements of dioxins concentrations and incinerator temperatures at the smokestack level (covering 96.6% of national MSW incinerators and 97.4% of the national incineration amount; Supplementary Table 2), which are the targets in the emissions standards policy; and unit information at the incinerator level regarding MSW treatment, power generation, incinerator type, treatment capacity, raw material input, control technology, age, geographical location and other individual features, which support a full exploration of specific measures to achieve the relevant emissions standards and impending ambitious programs. Using the CEAWI database, we conduct, at the unit level and on a national scale, not only an *ex post* evaluation of the compliance with the current standards in 2018 (presenting a detailed map of MSW-related dioxins pollution herein) but also an *ex ante* assessment of the potential effects of the full implementation of the recently announced plans on dioxins mitigation, environmental improvement and public health (noting effective measures and technologies). Regarding result validation, we compare our estimates using real measurements to previous inventories using average emissions factors (Tian et al., 2012; Zhou et al., 2018) and perform a comprehensive uncertainty analysis and independent atmospheric verification.

2. Methods

2.1 Construction of the CEAWI database

The CEAWI database is a new database for Chinese MSW incineration power plants, which uses actual official monitoring data derived from China's national EIA system and CEMS to estimate nationwide, unit-level dioxins emission and concomitant environmental and health impacts. The CEAWI dataset encompasses almost all MSW incineration power plants operating in mainland China (Supplementary Table 3), totalling 381 plants in 2018. We focus on dioxins because not only it is the target of the current emissions standards policy, but it is also classified as a Group 1 Carcinogen.

We compile and develop the CEAWI database by coupling two detailed national datasets for Chinese MSW incineration power plants provided by the Ministry of Ecology and Environment of China (MEEC): one with real measurements of dioxins concentrations (Construction Project Environmental Impact Assessment System) and incinerator temperatures (Open Platform for Automatic Monitoring Data of Municipal Solid Waste Incineration Power Plant) at the smokestack level and another with incinerator-level information regarding MSW treatment, power generation, incinerator type, treatment capacity, raw material input, control technology, age, geographical location and other individual features, which are monitored and recorded by China's national EIA system and CEMS. The combination of real measurements and unit-specific information facilitates the exploration of specific determinants and mitigation measures to achieve the relevant emissions standards and impending ambitious programs, as well as quantitative assessment of dioxins emission mitigation and associated environmental impacts and health risks.

2.2 Evaluation of compliance with the emissions standards

Using the above smokestack-level, actual official monitoring data of dioxins concentrations and incineration temperatures (the targets of the emissions standards policy in China), we explore the individual compliance of Chinese MSW incineration power plants. Furthermore, we quantify compliance based on two typical criteria, namely the compliance rate and compliance ratio (Tang et al., 2019). The compliance rate is defined as the proportion of complying observations (namely, smokestack concentrations within the current emissions standards and incineration temperatures above the required level of 850℃) in the total valid observations, ranging from 0% (representing an utter noncomplier at any time) to 100% (representing a full compiler throughout the entire sampling period) (Tang et al., 2020; Bo et al., 2021). Regarding the concentration standard, we specifically introduce the compliance ratio to measure the extent to which a given pollution concentration exceeds the limit (Tang et al., 2020; Bo et al., 2021), defined as:

$$R_i = \frac{S_i - C_i}{S_i} \tag{1}$$

where the subscript i indicates the incineration facility; S denotes the dioxins emission standards (ng TEQ m^{-3}), which is the upper limit of the allowed pollutant concentration; C denotes the dioxins smokestack concentrations in flue gas (ng TEQ m^{-3}), which is measured via field smokestack sampling from Chinese national EIA systems; and R is the estimated compliance ratio with a range of (-∞, 1), monotonically increasing with the increase of compliance improvement, and yielding a positive (or negative) value for compliance (or noncompliance).

2.3 Estimation of emission factors and emissions

The introduction of actual official monitoring data is conducive to the estimation of dioxins emission factors, which avoids the use of many indirect parameters and relevant assumptions applied in previous studies (Li et al., 2015; Li et al., 2016; Huang et al., 2016; Song et al., 2019):

$$EF_i = C_i \times V_i \tag{2}$$

where V denotes the theoretical flue gas rate, which can be estimated by comprehensive field measurements from China's first National General Census of Pollution Sources and expressed as the volume of flue gas per unit of the MSW incineration amount (Nm^3 $tonnes^{-1}$); and EF is the emission factor (or emission intensity), which is defined as the volume of emissions per unit of the MSW incineration amount (g TEQ $tonnes^{-1}$).

Notably, theoretical flue gas rates were calculated based on systematic field measurements conducted by the MEEC, which have been widely used in emission estimation for iron and steel, thermal power and cement industries (Tang et al., 2019; Tang et al., 2020; Bo et al., 2021; Tang et al., 2022); these studies also confirmed that theoretical flue gas rates generally approached their corresponding theoretical values (Tang et al., 2019; Tang et al., 2020; Bo et al., 2021; Tang et al., 2022). Furthermore, the introduction of theoretical flue gas rates can effectively prevent severe underestimation attributable to the lack of data on the flue gas volume (Tang et al., 2019).

The absolute dioxins emission of each Chinese MSW incineration power plant can be estimated by multiplying the activity level by the detailed emissions factors:

$$E_i = EF_i \times A_i \tag{3}$$

where E denotes the absolute dioxins emission (g TEQ) and A denotes the facility-level activity data, namely the volume of MSW treatment (tonnes), which is provided by the MEEC.

2.4 Estimation of future potential emission reductions

To explore the future dioxins emission reduction potential of China's MSW incineration power plants under different control policies, this study designed five future scenarios, including four individual policy scenarios (concentration standard tightening, technology upgrading, operation improvement and MSW sorting) and one comprehensive policy scenario (combining the above four policies).

Specifically, in concentration standard tightening scenario, according to the more stringent dioxins emission standard (0.05 ng TEQ m^{-3}) issued by Shenzhen and Hainan, we assume that this limit target will be implemented throughout the country in the future, and plants that do not meet the requirements of this standard will be upgraded in terms of technology upgrading and process optimization by reference to plants that have already met the standard limit requirements, to calculate the dioxins emission of national MSW incineration plants under this scenario. In the technology upgrading scenario, we assume that the plants will adopt the GFIs recommended by the MHURDC in the future, and the emission level after the transformation and upgrading of the FBIs can be referred to the average emission level of the current GFIs technology, to finally calculate the dioxins emission level after the transformation and upgrading of the furnace type technology. In addition, the incineration temperature affects the decomposition efficiency of dioxins (Zhao et al., 2022). When the incineration temperature reaches above 850°C, dioxins can be effectively decomposed, while the range of 500-800°C is the optimal synthesis temperature range for dioxins (Peng et al., 2022). In the operation improvement scenario, we assume that for target plants that are lower than the temperature standard requirements (850°C), the incineration temperature can be increased to above 850°C by adding auxiliary fuels or reducing the water content of water. The corresponding emission levels refer to the average emission concentration that has already met the temperature standard requirements, and then calculate their future emissions in the operation improvement scenario.

In the waste sorting scenario, Shanghai's waste sorting policy was selected as the policy target in this study, because it mainly achieved dioxins emission reduction through two ways. on the one hand, the waste sorting method in Shanghai affects the amount of MSW incineration by increasing the recovery rate. on the other hand, the separation of wet waste can effectively reduce the waste content of the incinerated waste, which will increase the caloric value of waste and incineration temperature, and ultimately achieved the purpose of inhibiting dioxins synthesis. Specifically, we assume that China's waste recycling rate will reach the status quo of waste recycling in developed countries in the future (Kaza et al. 2018), to predict future dioxins emission. In the meantime, we also determined the emission reduction effect by collecting the incineration temperature and dioxins concentration data before and after the implementation of Shanghai's waste sorting policy, to predict the dioxins emission after the nationwide promotion of this waste sorting method. In the comprehensive policy scenario, we assume that the lowest concentration that plants can reach under the above individual policy scenarios is the lower limit of the emission level under all policies implemented by the plants, and then combine with the activity level data of plants under the waste sorting scenario, we comprehensively assess the dioxins emission of plants under the comprehensive policy scenario.

2.5 Air quality model

We conduct the Comprehensive Air Quality Model with Extensions (CAMx) version 6.2, a three-dimensional, Eulerian air quality model to simulate dioxins emission in China. The CAMx model is approved by the US Environmental Protection Agency for simulating the emission, transport, chemistry, and removal of air pollutants in the atmosphere. The meteorological parameters are simulated using the Weather Research and Forecasting Model WRF-ARW version 3.9.1.1, with 35 sigma levels along the vertical direction and a horizontal grid resolution of 36 km. The initial and boundary conditions for the simulations are generated using the final operational global analysis dataset (with a horizontal resolution of 1°×1°, at 6-h intervals) obtained from the United States National Centres for Environmental Prediction and the National Center for Atmosphere Research. Land use, cover and topographical data are derived from the latest WRF input dataset at a 30-second resolution. The CAMx domain (160×200 grid cells) area is centered at (110°E, 35°N) and covers all of East Asia.

To explore the impact of dioxins emission originating from Chinese MSW incineration power plants on the air quality, the scenarios of current emissions in 2018 and future control programs are simulated. In the simulation process of each scenario, related emission inventories, meteorological fields and environmental conditions are adopted as the model inputs for the CAMx model. Accordingly, volume-average species concentrations in each grid are simulated via the CAMx model according to the Eulerian continuity equation. Furthermore, we evaluate the performance of the CAMx model, focusing on model-simulated dioxins concentrations versus daily measured observations in the corresponding grids (Construction Project Environmental Impact Assessment System).

2.6 Health risk assessment

Ingestion, inhalation and dermal contact with contaminated substances are the three main routes of human exposure to dioxins and body burden (Pius et al., 2020). In this study, we consider inhalation as the major exposure pathway for three reasons. First, regarding the dermal absorption and ingestion pathways, the transformation process from the pollutant concentration in air or soil samples to the corresponding dermal or ingestion doses is very complicated and uncertain, mainly due to the theoretical heterogeneity of the skin adherence factor, soil consumption rate, bioconcentration factor and consumption of polluted vegetables. Furthermore, the lack of localized survey data (instead of using default values) will also lead to the inability to distinguish heterogeneity among individuals. Second, compared to previous studies, in this study, we focus on nationwide MSW incineration power plants rather than a single-point pollution source. Therefore, a nationwide field sampling of MSW incineration plants seems unrealistic, and only the dioxins concentration in the atmosphere around all MSW incineration plants in China can be simulated by air quality models. Third, due to the unavailability of water and soil dioxins concentration data, the health risks resulting from both ingestion and dermal exposure routes cannot be calculated.

Therefore, the risk quotients model is introduced to evaluate the health risk of highly toxic pollutants stemming from Chinese MSW incineration power plants (USEPA, 2015). By superimposing spatial distribution data of the grid population density on exposure concentration data, population-weighted hazard index (HI) and carcinogenic risk (CR) values are calculated to characterize the noncarcinogenic and carcinogenic risks, respectively (Zhou et al., 2018).

$$HI_u = \frac{\sum_k (Sim_{k,u} / RfC) \times P_{k,u}}{\sum_k P_{k,u}} \tag{4}$$

$$CR_u = \frac{\sum_k (Sim_{k,u} \times SF_{inh}) \times P_{k,u}}{\sum_k P_{k,u}} \tag{5}$$

where the subscripts k and u denote the grid and region codes, respectively, with $k \in u$; HI_u denotes the population-weighted hazard index; $Sim_{k,u}$ denotes the simulated concentrations of dioxins; RfC is the reference concentration of dioxins for the noncarcinogenic risk (mg m^{-3}); $P_{k,u}$ is the population; CR_u indicates the population-weighted CR; and SF_{inh} denotes the inhalation slope factor for the CR (mg m^{-3})$^{-1}$. Therein, the data for RfC and SF_{inh} are obtained from the United States Environmental Protection Agency (USEPA, 2015).

2.7 Uncertainty analysis

We conduct an uncertainty analysis to verify the reliability of our estimates for dioxins emission in the Monte Carlo framework (Tang et al., 2019; Bo et al., 2021). In the estimation of dioxins, uncertainties might arise from errors during field measurement, use of theoretical flue gas rates and estimation of facility-based activity levels. To ensure the stability of dioxins detection instruments, the relevant standard (HJ77.2-2008) stipulates that the stability of instruments should be kept within the range of ±35%. Thus, we assume that dioxins concentrations can be generated using a uniform distribution around its measured concentration values within the allowed error range of the detection instruments (Bo et al., 2021). Regarding the uncertainty resulting from the use of theoretical flue gas rates, we assume that each flue gas rate is generated by following uniform distributions around corresponding theoretical values within the possible range (Tang et al., 2019). Regarding the uncertainty in facility-specific activity levels, we assume normal distributions with a 5% coefficient of variation (CV, defined as the standard deviation divided by the mean) for MSW incineration consumption by each facility (Bo et al., 2021). We employ the Monte Carlo approach to generate random values of dioxins concentrations, flue-gas rates and activity levels following their respective distributions. A total of 10,000 simulations are run to estimate the uncertainty ranges of the emission factors and absolute emissions (Tang et al., 2019; Bo et al., 2021).

3. Results

3.1 Current standards compliance

The monitoring data reveal extensive compliance with the new concentration standard, with 98.9% of all Chinese MSW incineration power plants in compliance and 99.3% lower smokestack dioxins concentrations than the national limit in 2018 on average (Fig. 1**e**; Supplementary Table 2). Regarding the stricter local standard, all policy targets (the incinerators in Shenzhen city) achieved compliance and even over-compliance (by 73.7% on average). Previous observations were sparse, and our results reflect a consistent decline in dioxins concentrations after enforcing the new standards in 2016, specifically by 59.7-90.1% (Ma et al., 2012), 94.5% (Ni et al., 2009), 84.0% (Liu et al., 2013), 65.0-97.2% (Zhang et al., 2012) and 75.0% (Lin et al., 2015) in a point-to-point comparison to field measurements for 2003, 2006, 2010, 2012 and 2015, respectively (Supplementary Table 4). However, only 66.7% of national incinerators fully met the operation condition-related requirement in 2018 (Fig. 1**g**), and 72.3% of the total daily incinerator temperatures were regulated in compliance with the temperature standard (Fig. 1**h**). Temperature compliance, in turn, could largely prevent incomplete combustion, rendering 56.4% lower dioxins concentrations than those under noncompliance ($p < 0.01$, 95% confidence interval (CI) = (-∞, -0.01)). Our analysis highlights technological upgrades as an important measure for standards compliance: grate firing incinerators (GFIs), a relatively environmentally friendly incineration technology, were employed at 83.2% of all plants in 2018 (with average dioxins concentration and incineration temperature of 0.018 ng TEQ m^{-3} and 934.58 ℃, respectively; light red dots in Fig. 1**a**), yielding 52.3% lower dioxins concentrations and 29.5% higher incinerator temperatures than those sustained by fluidized bed incinerators (FBIs) (deep red dots in Fig. 1**a**; with the corresponding dioxins concentration and incineration temperature of 0.038 ng TEQ m^{-3} and 721.65 ℃, respectively). Furthermore, dioxins control technology has commonly been installed at Chinese MSW incinerators, especially active carbon injection and bag filters that provide high removal efficiencies (95.5-99.7%) (Xu et al., 2009), which is also the main reason for the high compliance rate of Chinese MSW incineration power plants under the implementation of the new emission standard.

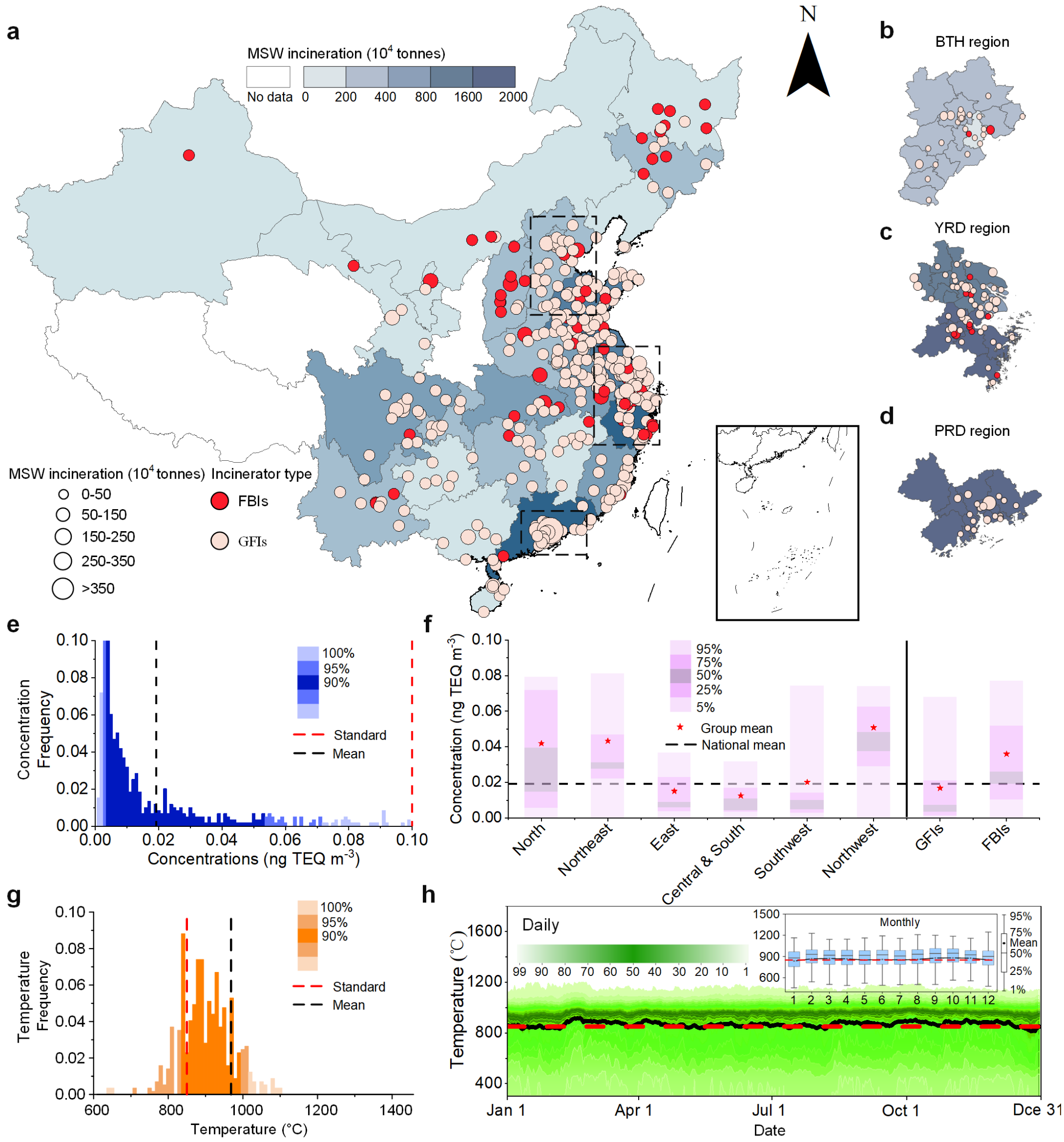

Figure 1 | Chinese municipal solid waste (MSW) incineration power plants. a-d, MSW incineration power plants operating in 2018 in mainland China (**a**) and the Beijing-Tianjin-Hebei (BTH; **b**), Yangtze River Delta (YRD; **c**) and Pearl River Delta (PRD) regions (**d**). The dots indicate individual plants, with the size representing the annual MSW incineration amount (10^4 tonnes) and the colour representing the employed incineration technology (fluidized bed incinerators (FBIs) or grate firing incinerators (GFIs)); the coloured background denotes the provincial MSW incineration amount. **e-h**, Distributions of the smokestack-level dioxins concentrations (ng toxic equivalent quantity (TEQ) m^{-3}) in China (**e**) and grouped by region and incineration technology (**f**), and distributions of the annual (**g**), daily (**h**) and monthly (**h** inset) average incinerator temperatures (°C). The black and red dashed lines indicate the national mean and associated current standards, respectively; the colour gradation indicates the intervals between the percentiles or quartiles; the red asterisks indicate the group means; and the black solid curves denote the daily mean.

As with general compliance with the current policies, the emissions intensities of Chinese MSW incineration power plants could be suitably controlled in 2018, averaging 156.4 ng TEQ tonnes^{-1} across the nation (black dashed lines in Figs. 2**e**,**f**) and 60.9-99.3% lower levels occurred at discrete plants than their respective previous values observed between 2006 and 2015 (green asterisks in Figs. 2**e**,**f**). Overall, the emissions intensities were better regulated at incinerators with a larger extent of concentration compliance (represented by the compliance ratio; Pearson's r = -0.99, p < 0.01; Supplementary Table 5) and under temperature compliance (by 63.0%; p < 0.01, 95% CI = (-∞, -77.70)). This could finely explain the observed spatial patterns: the lowest emissions intensities were observed in the provinces or municipalities of Chongqing, Henan, Shandong and Guangdong (reaching 45.6, 72.3, 75.1 and 75.3 ng TEQ tonnes^{-1}, respectively, in 2018; black points in Fig. 2**e**), where the plants exhibited the highest compliance (with compliance ratios of 93.2%, 96.0%, 92.5% and 89.7%, respectively). In the central and southern region (defined in Supplementary Table 2; purple bar in Fig. 2**f**) and eastern region (cyan bar in Fig. 2**f**), alongside the highest concentration compliance ratios (87.4% and 84.9%, respectively, compared to the lowest level of 49.2% in the northwestern region (blue bar in Fig. 2**f**)) and the largest shares of temperature compliers (85.0% and 84.6%, respectively, compared to the smallest share of 55.6% in the northwestern region), the emissions intensities were regulated at the lowest levels (104.3 and 133.1 ng TEQ tonnes^{-1}, respectively, compared to the value of 260.3 ng TEQ tonnes^{-1} in the northwestern region). Again, technological updates facilitated dioxins control, rendering lower emissions intensities at plants using GFIs (by 56.1%; p < 0.01, 95% CI = (-∞, -141.71)) and in provinces with higher GFI penetration (r = -0.35, p = 0.07).

Emissions intensity control greatly addressed the otherwise severe dioxins pollution originating from fast-growing, large-scale MSW incineration across China. Using the actual official monitoring data, we estimate the total dioxins emission of Chinese MSW incineration power plants at 19.6 g TEQ in 2018 (grey bar in Fig. 3**e**), which is very close to the 2017 level (19.0 g TEQ) (Fu et al., 2022). Moreover, our 2018 result is 16.7-90.9% lower than previous estimates between 2004 and 2015 (Supplementary Table 4) (Tian et al., 2012; Zhou et al., 2018; Li et al., 2021; Zhu et al., 2008), although Chinese MSW incineration grew by 3,082.9% from 2004 to 2018, reflecting a substantial mitigation effect under the new standards policy in recent years. Driven by this effect, although China ranked at the top as the world's largest MSW incineration producer (representing 44.8% of the global MSW production in 2018 (OECD, 2021)), its dioxins emission was far lower than those of countries with a lower share of MSW production, such as Canada (0.3%), Japan (12.3%) and Korea (1.8%) (UNEP, 2018). Furthermore, according to the daily MSW treatment capacity is divided into four categories, including Class extra-large (>2000 t/d), Class I (1200-2000 t/d), Class II (600-1200 t/d) and Class III (150-600 t/d). Our results show that the "extra-large" type of plant had the lowest level of dioxins emission factor, which is 9.8-32.4% lower than the other three categories. We also found that the dioxins emission factor of adding other fuels (such as bituminous coal or lean coal) to the waste was lower than that of burning pure waste components. This is mainly due to the high sulfur content in coal, which inhibits the synthesis of dioxins (Chen et al., 2008; Peng et al., 2020). In the meantime, doping auxiliary fuels such as coal in the MSW incineration can effectively increase the incineration temperature of the entire incinerator, which will be conducive to the decomposition of dioxins at high temperatures.

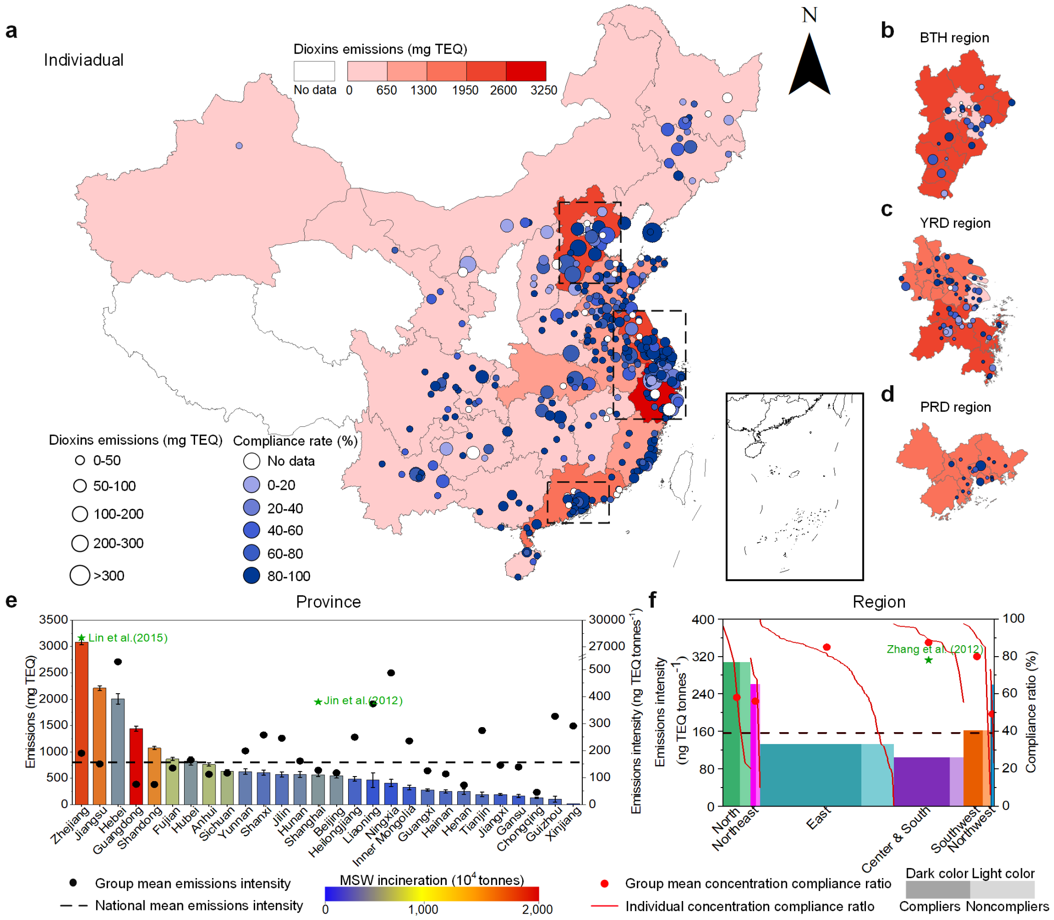

Figure 2 | Dioxins emission from Chinese municipal solid waste (MSW) incineration power plants. a-d, Individual emissions (mg toxic equivalent quantity (TEQ)) of MSW incineration power plants operating in 2018 in mainland China (**a**) and the Beijing-Tianjin-Hebei (BTH; **b**), Yangtze River Delta (YRD; **c**) and Pearl River Delta (PRD; **d**) regions. The dots indicate individual plants, with the size indicating emissions and the colour indicating the compliance rate (defined as the proportion of observations complying with the current standards); the coloured background denotes the provincial emissions. **e**, Provincial emissions (left *y* axis), with the colours of the bars denoting the MSW incineration amount (10^4 tonnes) and the error bars indicating 2 standard deviations of the emissions estimates. The black dashed line and points indicate the national and provincial means, respectively, of the emissions intensity (ng TEQ tonnes^{-1}; right *y* axis). **f**, Regional emissions, where the colour of the bars indicates the region, the height indicates the emissions intensity (left *y*-axis), the width is proportional to the MSW incineration amount, the area is proportional to the emissions level, and the shaded area is proportional to the emissions of standards compliers (dark) and noncompliers (light). The black dashed line indicates the national mean emissions intensity; the red curves and points indicate the individual and regional concentration compliance ratios (the exceedance of the smokestack concentration standard; right *y* axis), respectively. The green asterisks denote the previous sparse observations of the emissions intensities in the associated provinces (Ni et al., 2012; Jin et al., 2012) (**e**) and regions (Zhang et al., 2012) (**f**).

Super-polluting plants often incinerate a large amount of MSW, but the mitigation effect also largely shapes the final map of dioxins emission. On the one hand, provincial emissions were strongly related to the proportions of plants ($r = 0.77$, $p < 0.01$; Fig. 2**a**) and the MSW incineration amount in the associated province ($r = 0.79$, $p < 0.01$; Fig. 2**e**). This pattern also holds regionally: the eastern region (cyan bar in Fig. 2**f**), accounting for the bulk of the plants (53.5%) and MSW incineration amount (49.3%), produced the largest share of dioxins emission in 2018 (44.0%). Our results also point to the three developed economic zones of the Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD) regions as emissions hotspots (jointly accounting for 46.9% of the national dioxins emission), in proportion to their large-scale MSW incineration (accounting for 44.7% of the national treatment scale; Figs. 2**b-d**). The dominance of MSW incineration and dioxins emission reflects the high levels of economic development, population and urbanization in the associated regions ($r \geq 0.48$, $p < 0.01$; Supplementary Table 5). On the other hand, mitigation accompanied by extensive standards compliance was also effective. For example, Guangdong and Shandong provinces accounted for 15.2% and 10.6% of the MSW incineration amount, respectively, but generated only 7.3% and 5.5% of dioxins emission, respectively, by virtue of their 51.9% and 52.0% lower emission intensities, than the national mean (Fig. 2**e**). Featuring the best-controlled emissions intensities, the central and southern region (purple bar in Fig. 2**f**) produced 11.5% lower dioxin emissions than those produced in the northern region (conversely, with the highest emission intensities; green bar in Fig. 2**f**) while incinerating 150.9% more MSW. Our analysis repeatedly highlights the importance of technology updates, with GFI-equipped plants accounting for 83.2% of the Chinese MSW incineration amount but only 66.6% of the total dioxins emission (Fig. 2**a**). Furthermore, the results also show that there is a linear correlation ($r = 0.50$, $p < 0.01$) between the annual MSW incineration amount and power generation at the plant level, indicating that the higher the MSW incineration amount, the greater the power generation. Similarly, there is a similar correlation relationship ($r = 0.43$, $p < 0.01$) between annual power generation and dioxins emission, reflecting that plants with higher power generation have higher incineration amounts, leading to higher levels of pollution emissions. Daily treatment capacity is highly correlated with pollutant emissions ($r = 0.44$, $p < 0.01$), and incineration treatment capacity determines the annual incineration scale of the plant, and also indirectly reflects the pollutant emission level.

3.2 Future emissions mitigation

Given the well-controlled dioxins pollution observed after the enforcement of the new standards in 2016, we further assess the potential abatement resulting from the implementation of the ambitious plans regulating MSW-related pollution. By assuming that all Chinese MSW incinerators meet the 50% stricter local concentration standard, achieve the current temperature standard at the five-minute level (MEEC, 2019), and install the required GFIs and pollution control while maintaining production at 2018 levels and that the waste sorting program is extended nationwide, we project synergistic decreases in the overall smokestack concentrations by 44.6% (to an average of 12.4 pg TEQ m^{-3}), emissions intensities by 45.3% (to an average of 85.6 ng TEQ $tonnes^{-1}$) and absolute emissions by 67.7% (to a total TEQ of 6.3 g; Fig. 3). Nevertheless, fully accomplishing these plans across all Chinese MSW incineration power plants may be challenging, given that 33.3% of plants (covering 27.9% of the MSW incineration amount) did not yet achieve full compliance with the current standards at the end of 2018. Encouragingly, 2.3% of plants had already reached all future program goals by 2018, and the waste sorting scheme has been implemented in 46 pilot cities by 2020 (NDRC, 2021), supporting the technical feasibility and operational viability of these ambitious plans and revealing a pathway (and specific measures and technologies thereof) for other plants and cities to follow.

There still exists much room for improvement among Chinese MSW incineration power plants, which are projected to reduce smokestack concentrations, emissions intensities and absolute emissions by 27.1%, 28.0% and 27.5% (equivalent to 40.6% of the total potential), respectively. Even reaching the world's strictest level, the current dioxins concentration standard can be further tightened, at least to the 50% stricter local standard already met by 95.5% of plants in 2018. This effort can reduce dioxins concentrations, emissions intensities and emissions by 5.5%, 5.2% and 5.0%, respectively (patterned blue bar in Fig. 3**e**). In incinerator renovation, technological updates are a leverage point: for example, introducing already prevalent GFIs into non-users (accounting for 16.8% of all plants in 2018) can facilitate potential reductions in smokestack concentrations, emissions intensities and absolute emissions by 15.5%, 16.5% and 17.6%, respectively (patterned orange bar in Fig. 3**e**). A considerable opportunity for encouraging future abatement is operation condition improvement: higher incinerator temperatures, which can effectively prevent incomplete combustion, facilitated lower dioxins concentrations in 2018 (r = -0.38, $p < 0.01$; Supplementary Table 5). Accordingly, the Chinese government has stipulated that every five-minute average should comply with the temperature standard since 2020, without defining a clear frequency-related requirement previously. However, only 2.9% of plants met this new requirement in 2018, and we expect reductions in smokestack concentrations, emission intensities and emissions by 20.8%, 21.7% and 21.1%, respectively, under the overall achievement (patterned yellow bar in Fig. 3**e**).

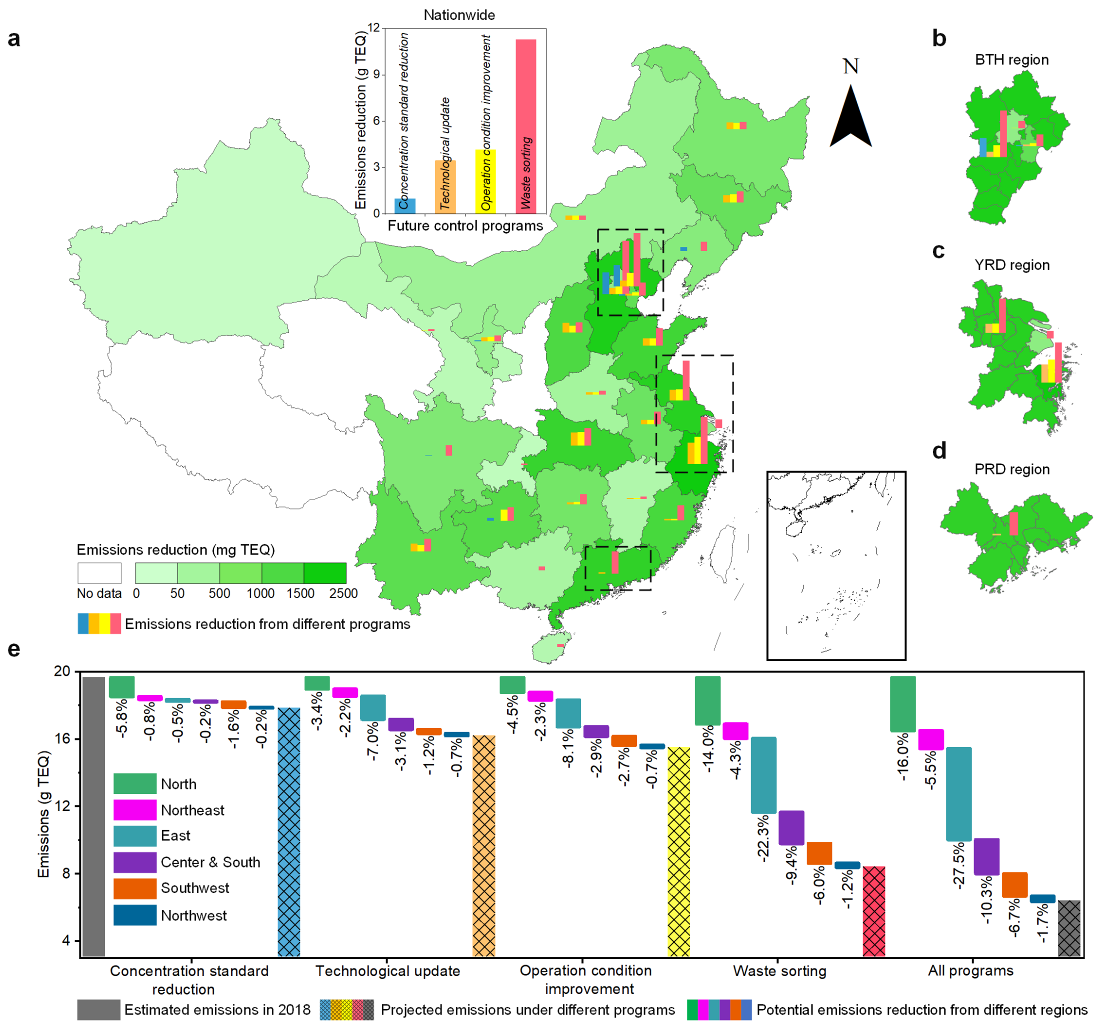

Figure 3 | Potential dioxins emission reductions. a-d, Projected reductions in the dioxins emission of municipal solid waste (MSW) incineration power plants in mainland China (**a**) and the Beijing-Tianjin-Hebei (BTH; **b**), Yangtze River Delta (YRD; **c**) and Pearl River Delta (PRD; **d**) regions under full implementation of the recently promulgated plans regulating MSW-related pollution. The coloured background indicates the potential provincial mitigation (mg toxic equivalent quantity (TEQ)); the bars indicate the potential mitigation attributable to the policies of concentration standard reduction (blue), technological update (orange), operation condition improvement (yellow) and waste sorting (red) in the associated provinces or nationwide (**a** insert). **e**, Projected reductions in the dioxins emission in the different regions. The nonpatterned grey bar indicates the estimated emissions in 2018; the patterned bars indicate the projected emissions under the implementation of the associated plans (bright colours) or all considered plans (grey); the bars between the grey and patterned bars indicate the projected emissions reductions in the associated regions.

Our results emphasize the promise of the waste sorting program, alone reducing overall smokestack concentrations, emissions intensities and absolute emissions by 27.1%, 27.1% and 57.4% (notably, 84.7% of the total projected abatement; patterned red bar in Fig. 3**e**), respectively. To constrain the country's large-scale, fast-growing MSW sector, the Chinese government has required MSW sorting into recyclable, household food, hazardous and other waste fractions in Shanghai since July 2019 (SMPG, 2019), in Beijing since May 2020 (PGBM, 2021) and in other 44 pilot cities by the end of 2020 (NDRC, 2021). Through the extraction of recyclables from waste materials, MSW sorting greatly facilitates waste recycling and MSW reduction: the overall waste recycling rate in the 46 pilot cities reached 30.4% in 2020 (NDRC, 2020) (approaching the 2025 nationwide goal of over 35% defined by the Chinese government (MHURDC, 2022)); the increasing trends of MSW production in Shanghai and Beijing for the years before the introduction of MSW sorting (by 5.6% and 3.7%, respectively) changed into declining trends in the years after the introduction (by 4.3% and 21.1%, respectively). Assuming carrying out MSW sorting nationwide (and reaching a waste recycling rate at the highest achievable level using the same waste sorting method), we project potential decreases in the Chinese MSW incineration amount by 41.7% and consequent dioxins emission by 40.1%. Furthermore, our analysis strongly recommends household food waste sub-sorting into dry and wet waste fractions, which is exclusively employed in Shanghai's pilot and has enhanced incinerator temperatures by 13.8% ($p = 0.10$, 95% CI = $(-\infty, 7.60)$) and reduced dioxins concentrations by 31.6%, probably by lowering the MSW chlorine and water contents (Shi et al., 2008; Cheng and Hu, 2010b; Lou et al., 2015). If this dry-wet waste segregation method is adopted in the national MSW sorting scheme, we project that the total emissions will additionally decline by 28.1%.

With these efforts, greater potential reductions (patterned grey bar in Fig. 3**e**) correspond to more polluting plants with higher smokestack concentrations ($r = 0.77$, $p < 0.01$) and larger MSW incineration amounts ($r = 0.40$, $p < 0.01$; Supplementary Table 5). Thus, the eastern region (cyan bars in Fig. 3**e**), exhibiting both the most inferior plants needing improvements in the future (representing 42.1% of the total nationwide number) and the highest MSW production level (48.5%), will contribute the largest proportion to the total potential (40.7%) across all regions—more specifically, both the largest contribution proportions via plant improvement (31.9%) and MSW sorting (38.9%). The highest-polluting plants were mostly allocated in the northern region (with 121.8% higher smokestack concentrations than those in the other regions; $p < 0.01$, 95% CI = $(20.13, \infty)$), such that northern plants (green bars in Fig. 3**e**), even only accounting for 10.0% of the total plants and 10.3% of the total MSW incineration amount, will account for a leveraged share of the potential reductions (23.6%, ranking 2nd behind the eastern region). The three highly populated BTH, YRD and PRD zones are MSW-producing centers, where the MSW sorting policy will generate a striking effect, alone leading to a 57.7% decline in emissions (pink bars in Figs. 3**b-d**)—which is equivalent to the majority (85.9%) of the final multi-measure-based potential in the three regions and accounts for nearly half (47.2%) of the MSW sorting-related potential across China.

3.3 Environmental and health benefits

Our air quality simulations project that the future MSW-targeted policies will deliver consistent environmental improvements throughout China. Compared with the measured concentration (with an average value of 0.085 pg m^{-3}), the simulated dioxins concentration in the atmosphere of the air quality model is significantly lower than the measured concentration, mainly because the dioxins in the real air from multiple anthropogenic emission sources, such as steel production, mobile transportation, and pesticide herbicide use (Yi et al., 2014; Zhan et al., 2019; Vernez et al., 2023). Ambient concentration reductions primarily rely on future emissions mitigation (r = 0.57, p < 0.01), such that greater abatements will occur in the eastern region (a reduction of 2.6×10^{-5} pg m^{-3} in the area-wide mean concentration) and BTH, YRD and PRD zones (reductions of 3.0×10^{-5}, 6.6×10^{-5} and 2.5×10^{-5} pg m^{-3}, respectively), particularly in the MSW-dense cites in these areas (such as both Jiaxing and Huzhou in the eastern region and YRD, with reductions of 7.2×10^{-5} and 7.0×10^{-5} pg m^{-3}, respectively). Considering demographic features, the population-weighted concentration reductions will still be notable in the eastern region (by 1.5×10^{-8} pg m^{-3}) and three developed zones (by 3.2×10^{-8} pg m^{-3} versus 1.4×10^{-8} pg m^{-3} for the national mean) due to the overlap of notable population and emissions reductions. The populous core cities of Shanghai and Suzhou, located in the eastern region and YRD, respectively, exhibited the highest population-weighted dioxins pollution level across all the cities nationwide (at 1.6×10^{-6} and 8.0×10^{-7} pg m^{-3}, respectively) and will, in turn, obtain the highest air quality benefits (with reductions of 8.6×10^{-7} and 4.7×10^{-7} pg m^{-3}, respectively).

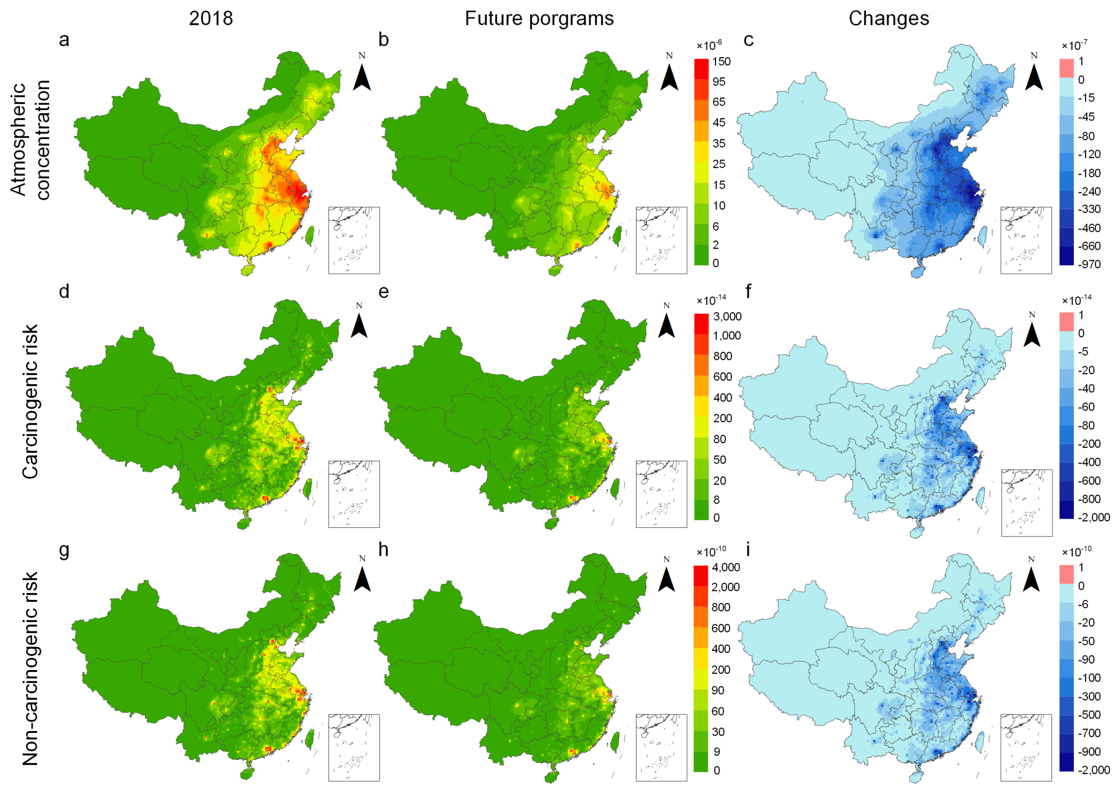

Figure 4 | Air quality and health benefits. a-i, Spatial distributions of the dioxins concentrations in the atmosphere attributable to Chinese municipal solid waste (MSW) incineration (pg m^{-3}; **a**,**b**) and the concomitant carcinogenic risk (**d**,**e**) and noncarcinogenic risk (**g**,**h**) in 2018 (**a**,**d**,**g**) and under the policy scenario assuming the full implementation of the recently promulgated future plans targeting MSW-related pollution (**b**,**e**,**h**), as well as the associated variations (policy scenario minus the baseline; **c**,**f**,**i**).

The health risk attributable to dioxins pollution originating from Chinese MSW incinerators has already been suitably controlled in 2018, following extensive compliance with the new standards. Based on the actual official monitoring data, the population-weighted CR and noncarcinogenic risk (represented by HI) are estimated at 1.5×10^{-13} and 1.6×10^{-9}, respectively, on average (Fig. 4**d**,**g**), with all the nationwide estimates 5 and 7 orders of magnitude lower, respectively, than the safe levels of 1.0×10^{-6} ($p < 0.01$, 95% CI = ($-\infty$, 1.60×10^{-13})) and 1 ($p < 0.01$, 95% CI = ($-\infty$, 1.76×10^{-9})), respectively. In a point-to-point comparison to previous estimates, we find a clear decline in health risk in recent years (Supplementary Table 4)—specifically, compared to estimates for 2006 (Li et al., 2014), 2008 (Deng et al., 2020), 2015 (Li et al., 2016) and 2017 (Deng et al., 2020), the CR declined by 1.1×10^{-5}-2.1×10^{-5}, 1.0×10^{-5}-1.4×10^{-5}, 2.0×10^{-10}-1.3×10^{-8} and 7.2×10^{-6}-1.8×10^{-5}, respectively, and compared to 2008 (Li et al., 2014), 2011 (Hao et al., 2018; Deng et al., 2020), 2015 (Deng et al., 2020) and 2017 (Deng et al., 2020) values, the HI decreased by 1.7×10^{-2}-$2.3\times10^{-}$

^{2}, 3.8×10^{-6}-3.2×10^{-1}, 1.2×10^{-7}-6.1×10^{-5} and 1.2×10^{-2}-2.9×10^{-2}, respectively. More encouragingly, while incinerating the largest proportion of the global MSW amount (44.8% in 2018), China exhibited an otherwise lower dioxin-related health risk than that in many developed countries burning considerably less MSW, such as Spain and Italy (accounting for only 11.6% and 19.0%, respectively, of the global MSW incineration amount but with 7 and 4 orders of magnitude higher health risks, respectively, than those in China in terms of both the CR and HI) (Cangialosi et al., 2008; Paladino et al., 2017). The health risk was highly sensitive to the ambient dioxins pollution level ($r = 0.79$, $p < 0.01$) and thus was notable in the eastern region and three developed zones (with 320% and 331% higher area-wide CR and HI values, respectively, than the nationwide levels). However, mismatches occur: the provinces of Henan, Jiangxi and Shaanxi exhibited disproportionately (7, 34 and 76 times, respectively) higher health risks than those in their counterparts of Hainan, Gansu and Qinghai, respectively, emitting equivalently small amounts of dioxins (accounting for only 1.0%, 0.8% and 0.0%, respectively, of the national emissions), probably as a result of transboundary transport of dioxins emission from adjacent regions. A similar phenomenon occurred in Guangdong, which produces 11.1% lower dioxins emission per unit area of urban land than the national mean but suffers a 3 times higher health risk, primarily because of the 138.1% higher population density.

Nevertheless, these well-controlled health risks will be substantially improved under the implementation of the ambitious but feasible MSW-regulating plans. The reduced exposure to dioxins pollution (Fig. 4**c**) will lead to an average decline of 62.6% in the health risk, more specifically, reductions of 9.2×10^{-14} and 1.0×10^{-9} in the CR and HI values, respectively (Figs. 4**f**,**i**). With this effect, the CR and HI values in China associated with MSW incineration-related dioxins pollution will be strictly controlled at an extremely low level (Figs. 4**e**,**h**)—not only far below the maximum allowed levels (by 8 and 10 orders of magnitude, respectively) but also far below all latest available observations in other countries or jurisdictions (by 3-8 and 6-8 orders of magnitude, respectively; Supplementary Table 4). Health benefits correspond to environmental improvements ($r = 0.61$, $p < 0.01$), with greater risk reductions again in the eastern region (by 5.5×10^{-13} and 6.0×10^{-9} for the CR and HI, respectively) and the BTH, YRD and PRD regions (by 5.7×10^{-13}, 1.0×10^{-12} and 7.8×10^{-13} for the CR, respectively, and 6.3×10^{-9}, 1.1×10^{-8} and 8.5×10^{-9} for the HI, respectively). Within these regions, the municipalities of Shanghai, Suzhou and Dongguan will benefit the most from the proposed future plans across all Chinese cities (with the CR reducing by 3.1×10^{-12}, 2.9×10^{-12} and 2.6×10^{-12}, respectively, and the HI reducing by 3.4×10^{-8}, 3.2×10^{-8} and 2.8×10^{-8}, respectively), which reflects the co-occurrence of notable mitigation effects and dense populations in these cities.

4. Discussion

With the use of these actual official monitoring data, our *ex post* analysis reveals the effectiveness of the new standards enforced in 2016 targeting Chinese MSW incinerators (the strictest globally); nearly all Chinese plants complied with the dioxins concentration standard, rendering the associated health risk at a safe level throughout China. In addition to dioxins, we also observe overall compliance with air pollution standards: according to CEMS-monitoring data, 98.5%, 99.1%, 99.2%, 96.0% and 99.3% of plants controlled their smokestack concentrations of particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxide (NO_X), carbon monoxide (CO) and hydrogen chloride (HCl), respectively, below the allowed upper limits in 2018. This extensive compliance was largely a result of oversight via the two national monitoring networks (namely, the EIA system and CEMS networks), which could be further enhanced in the future (for example, by involving dioxins in the CEMS for real-time monitoring (CAEPI, 2020)) and could be extended to greenhouse gas emissions (by involving CO_2 in the EIA system at least as already proposed in 2021 (MEEC, 2021) and even in the CEMS as adopted in the US (Burney, 2020). We find that end-of-pipe technology installation was an important measure to meet the emissions standards: by 2018, all plants had deployed advanced equipment such as activated carbon injection (installed at 95.7% of the total plants) and bag filter facilities (99.7%) to control dioxins and achieved denitrification (80.5%), deacidification (100%), bag filtering (99.7%) and activated carbon treatment (95.7%) to purify flue gases, which highlights the importance of technology updates in the future (for example, upgrading to powdered activated carbon for dioxins abatement (MHURDC, 2020). We find that there is no significant positive relationship between the operating days of plants and the dioxins emission factors ($r = 0.22$, $p > 0.05$), indicating that the emission factors may be more related to technological innovation, operating conditions, and waste components, but not directly related to the operating days of plants. Our simulations reveal a low health risk level associated with the current dioxins pollution stemming from Chinese MSW incineration; nevertheless, a national environmental risk management system should be developed to regularly monitor the environmental and health impacts of dioxins emission (as ranked in the second batch of the Chinese Priority Controlled Chemicals List) (MEEC, 2020).

In future dioxins management, our *ex ante* assessment projects substantial environmental and health benefits provided by the waste sorting program (contributing to the majority of the abatement potential) and, therefore, we suggest the establishment of a fine source separation and recycling system across China, particularly sorting wet waste (to enhance incinerator temperatures) (MEEC, 2022), chlorinated plastics (to reduce dioxins production) (MEEC, 2020) and metallic catalysts containing copper and cobalt ions from incinerated MSW (to avoid dioxins formation) (Cai et al., 2022). Furthermore, operation condition improvements represent a leverage point to improve Chinese MSW incineration plants, one-third of which had not met the current incinerator temperatures standard in 2018; therefore, severe penalties should be imposed on noncompliance (for example, in terms of reducing or even withdrawing government subsidies (MEEC, 2020)) to stimulate temperature-related compliance. In addition to the two promising measures, our results also highlight the importance of technology updates and standard tightening, where a system of policy instruments is needed to facilitate the full realization of all these different plans, covering a variety of administrative instruments (such as backward production capacity reduction (MEEC, 2016)) and economic instruments (such as financial incentives or penalties (MEEC, 2020), pollutant discharge permit trading (MEEC, 2019), credit and loan support (MEEC, 2022) and preferential taxes (MFC, 2021). Our results demonstrate a productive effort in MSW-dense regions (especially East China and the developed economic zones of the BTH, YRD and PRD regions), which should be prioritized in future management efforts (MEEC, 2021).

By introducing real measurements obtained from the two national monitoring networks of the EIA system and CEMS, our CEAWI dataset represents a major advancement in reducing the estimation uncertainty and enhancing the spatiotemporal resolution. The uncertainty analysis shows that our estimates of dioxins emission exhibit a relatively low uncertainty level, with a 95% CI of ±0.03% (versus ±2.62% for existing inventories (Zhou et al., 2018)). Furthermore, we conduct an independent verification and find that the simulated dioxins concentrations are generally consistent with the monitoring values of the MEEC ($r = 0.52$, $p < 0.01$). We demonstrate the use of the CEAWI database by analysing detailed dioxins emission as well as associated environmental impacts and health risks considering both current and future policies targeting MSW-related pollution. Given that dioxins, as a type of persistent organic pollutant, can be hardly degraded but can easily be transmitted into the atmosphere over long distances (Martínez et al., 2022), dioxins control will result in global benefits and require multinational efforts; our unit-level, comprehensive estimates and projections could offer helpful insights into future policy making for not only China but also other countries suffering from high MSW and dioxins pollution level (such as India (Kumari et al., 2019) and Brazil (de Lacerda et al., 2019)).

In addition, we have noticed that the United States is gradually shutting down some MSW incineration power plants, and the European Investment Bank has announced to stop supporting the investment of MSW incineration construction projects. They believe that incineration power plants should be gradually closed for the following three reasons. First, incinerators produce toxic ash and sludge and emit toxic chemicals (such as dioxins, furans and mercury), which will endanger human health and well-being. Second, incinerators emit a large amount of greenhouse gases, accelerating global climate deterioration. Third, on the vast and available land resources, priority should be given to implementing landfill and composting methods, which are far less harmful to the environment and health than incineration. The attitude of foreign countries towards MSW incineration will have a certain impact on China's future construction planning of incineration power plants. The Chinese government may change its attitude towards incineration treatment method, and then re-examine the impact of incineration on the environment, health and climate change from the following three aspects. Whether pollution emissions from China's MSW incineration plants have an inestimable impact on the environment, health and climate change? Whether China's current end-of-life governance technologies, operation conditions, and disposal measures can provide a safe living environment for people? How about the advantages and disadvantages of Incineration, landfill, compost and other methods in terms of operating costs, social benefits and sustainable development based on China's national conditions and future development goals? This study attempts to provide a reference for the planning and layout of plants by comprehensively evaluating the impact of MSW incineration emissions in China from the perspective of emission, environment and health.

5. Conclusion

This study introduced the national, plant-level, multi-source and latest measured emission concentration data, proposed a bottom-up emission estimation method, and combined with the production information of plant and basic information, to construct the dioxins emission database of China's MSW incineration power plants, and systematically assess the impact of dioxins emission on air quality and human health under the current and future scenarios. Our results found that in 2018, the dioxins emission concentration of most MSW incineration power plants in China met the requirements of the new emission standard (GB 18485-2014). At the emission level, the average dioxins emission intensity and annual emission in 2018 were 156.4 ng TEQ t^{-1} and 19.6 g TEQ, respectively, which showed a significant downward trend compared with previous studies. At the spatial distribution, emission hotspots were located in China's east coast and densely populated areas such as the eastern region, the Beijing-Tianjin-Hebei, the Yangtze River Delta and the Pearl River Delta zones. At the health risks assessment, the health risks attributable to dioxins pollution originating from Chinese MSW incinerators have already been suitably controlled in 2018 and are far below the safety risk level. At the future emission reduction potentials, fully achieving both current emission standards and future regulations will reduce emissions and health risks by 67.7% and 62.6%, respectively, with waste-sorting programs contributing the majority.

Although the current levels of pollution from MSW incineration power plants in China and the associated health risks are at safe levels, we strongly recommend further comprehensive implementation of waste sorting policies, especially dry and wet waste separation methods similar to those in Shanghai. Furthermore, it is suggested to reduce the water content of the waste from the source, increase the temperature of the entire incinerator and ultimately promote the complete decomposition of dioxins. In the meantime, given the spatial heterogeneity of dioxins emission, it is suggested that future emission reduction policies should focus on the eastern coastal areas and the three developed economic zones, and further achieve the goal of sustainable emission reduction through the identification of these emission hotspots. In addition, it is worth noting that the composition of waste, start-up and shut-down periods, operating conditions, regional climate and temperature will bring uncertainty to the emissions estimation. In conclusion, this study reveals substantial benefits from curbing MSW-related dioxins pollution and underscores the promise of ongoing management.

Author statement

Jing Guo: Data Curation and Analysis, Software, Visualization, Writing-Original draft preparation, Writing-Reviewing and Editing. **Xin Bo**: Conceptualization, Supervision. **Yang Xie**: Methodology, Writing-Reviewing and Editing. **Ling Tang**: Conceptualization, Methodology, Supervision, Writing-Reviewing and Editing. **Jun Xu**: Software, Methodology. **Zhongzhi Zhang**: Software, Methodology. **Ruxing Wan**: Data curation, Visualization. **Haiyun Xu**: Investigation, Supervision. **Zhifu Mi**: Conceptualization, 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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