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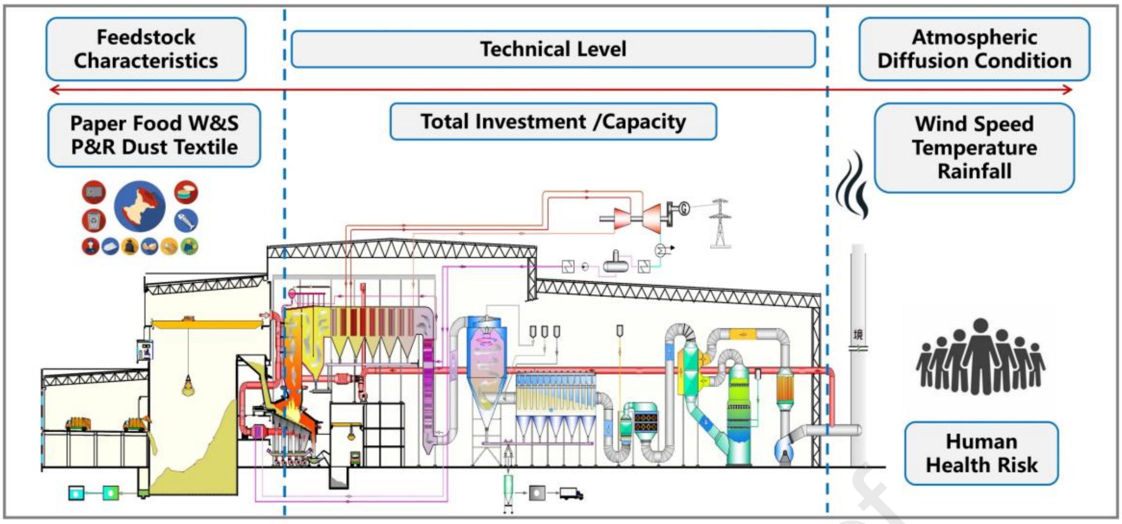
Feedstock Characteristics
Technical Level
Atmospheric Diffusion Condition
Paper Food W&S P&R Dust Textile
Total Investment /Capacity
Wind Speed Temperature Rainfall
Human Health Risk

Health risk assessment of municipal solid waste incineration emissions based on regression analysis

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Abstract

This study examined the potential health risks posed by the operation of 96 waste-to-energy (WtE) plants in 30 cities in the Bohai Rim of China. Utilizing a sophisticated simulation approach, the Weather Research and Forecasting (WRF) model coupled with the California Puff (CALPUFF) model, we obtained the spatial distribution of pollutants emitted by WtE plants in the atmosphere. Hazard indices (HI) and carcinogenic risks (CR) were calculated for each plant using the United States Environmental Protection Agency's recommended methodologies. The results indicated that both HIs and CRs were generally low, with values below the accepted threshold of 1.0 and 1.0×10^{-6}, respectively. Specifically, the average HI and CR values for the entire study area were 2.95×10^{-3} and 3.43×10^{-7}, respectively. However, some variability in these values was observed depending on the location and type of WtE plant. A thorough analysis of various parameters, such as waste composition, moisture content, and operating conditions, was conducted to identify the factors that influence the health risks associated with incineration. The findings suggest that proper waste sorting and categorization, increased cost of construction, and elevated height of chimneys are effective strategies for reducing the health risks associated with incineration. Overall, this study provides valuable insights into the potential health risks associated with WtE plants in the Bohai Rim region of China. The findings can serve as useful guidelines for law enforcement wings and industry professionals seeking to minimize the risks associated with municipal solid waste (MSW) management and promote sustainable development.

Keywords: Incineration; WRF/CALPUFF; Health risk assessment; Ridge regression model; MSW classification

1. Introduction

China's rapid economic growth and accelerated urbanization have led to a significant increase in municipal solid waste (MSW), posing a growing challenge to human health. To address this issue, the Chinese government has actively promoted waste-to-energy (WtE) plants due to their benefits, including land conservation, high efficiency in MSW reduction, and lower greenhouse gas emissions[1-4]. As a result, the number of WtE plants doubled between 2017 and 2021, with a total capacity of 180.2 million tons in 2021[5, 6]. Currently, incineration accounts for 72.54% of MSW disposal in China, with a growth rate of 25.92%[6, 7]. This highlights the increasing importance of WtE plants in China's waste management strategy.

However, the operation of WtE plants generates a substantial amount of air pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NOx), heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans (PCDD/Fs). Exposure to these pollutants via inhalation can result in a wide range of adverse health effects, such as respiratory problems, cardiovascular disease, and even cancer[8-17]. For instance, studies have linked exposure to PAHs and PCDD/Fs, which are byproducts of incomplete combustion, to immune system suppression, thyroid disruption, and other serious health issues[16-21]. Considering the potential health risks associated with WtE plant emissions, it is essential to identify and implement effective measures to mitigate these risks.

Many studies have expressed concerns about the health impacts of incineration. To better understand these risks, researchers first need to establish an emission inventory to measure the amounts of air pollutants released by WtE plants. This involves collecting data on Emission Factors (EFs) to accurately represent local emissions[22, 23]. In China, numerous field tests were conducted to determine EFs for various WtE plants. Using this data, Fu et al.[24] developed an emission inventory for MSW incineration in China spanning from 2006 to 2017, providing a comprehensive view of the characteristic emissions of WtE plants. Subsequently, researchers employed air diffusion models like

WRF/CALPUFF[14, 25, 26] and Gaussian Plume Model[8, 15] to estimate the spatial distribution of WtE plants' air pollutants. WRF is a mesoscale numerical weather prediction system used for atmospheric research, which can provide real meteorological field data across scales from tens of meters to thousands of kilometers[27]. CALPUFF is an accurate 3D unsteady lagrangian diffusion model system for simulating pollutant diffusion and conversion[28]. Compared with the traditional Gaussian Model, CALPUFF performs much better in complex terrain and various wind conditions (strong wind, stagnation, inversion, recirculation, etc.)[14, 25, 26]. Finally, Health Risk Assessment (HRA) models, developed by the US Environmental Protection Agency (USEPA), were utilized to evaluate the health effects of these pollutants[9, 29-32]. For instance, Zhou et al.[8] established an emission inventory for WtE plants in China in 2015 based on literary investigations, then used Gaussian Plume Models to calculate Hazard Indices (HI) and Carcinogenic Risks (CR) across different regions. By taking these steps, scientists could better understand the potential health consequences of WtE plant emissions.

However, in previous studies, the emission inventories obtained by field tests were limited by the workload, which can only reflect the real pollution emission situation of a few waste-to-energy (WtE) plants during the sampling period. In addition, the emission inventories based on literature investigation can not distinguish the difference in emission factors among WtE plants. There was a significant gap in systematic and comprehensive real-time pollutant measurement of WtE plants, which can accurately reflect real-time pollutant emissions from all WtE plants. At the same time, the application of air diffusion models necessitated extensive hardware facilities and meteorological data. Data collection and simulation often result in complex work and delayed feedback. Few studies have focused on a fast and efficient method for health risk assessment of incineration. In addition, existing health risk assessments of WtE plants were usually derived from the calculations of pollutant emission inventories, meteorological data, and the HRA model. Few studies explored the direct response relationship between health risk determinants and health risk, making it challenging to explore specific measures for reducing WtE plants' health risks.

As one of the most important economic and population centers of China, the Bohai Rim, encompassing 5 provinces/municipalities (Beijing, Tianjin, Hebei, Shandong, and Liaoning), exhibits high MSW production per capita and a large quantity of MSW incinerated per capita. Specifically, the MSW production per capita and quantity of MSW incinerated per capita in the Bohai Rim were 18.52 t/pop and 13.50 t/pop, representing 5.22% and 5.85% of China[6]. Besides, the population density in the Bohai Rim was 3.3 times that of China[14]. Therefore, the Bohai Rim was selected as the research area in this study.

In addition, in order to reflect the pollutant emission levels of WtE plants more accurately and realistically, the EFs in this study were calculated using systematic, actual measured pollutant concentration data extracted from China's Continuous Emission Monitoring Systems (CEMS) network[14]. This dataset, established by the Ministry of Ecology and Environment of China (MEE), provided nationwide, detailed, real-time pollutant emissions and other operation information from WtE plants since January 2020.

In order to address the knowledge gaps related to the health impacts of WtE plants, this study primarily investigated 96 WtE plants in the Bohai Rim and set the following research objectives: 1) An emission inventory was established for 2020 based on detailed operation information and pollutant concentrations from CEMS networks.2) The WRF/CALPUFF model was used to simulate the diffusion and deposition of air pollutants emitted by WtE plants, and the population-weighted HI and CR were calculated by the HRA model.3) Ridge regression analysis was used to examine the relationships between health risk determinants and the HI and CR, considering factors such as the quantity of MSW components incinerated, the technological level of the WtE plants, and atmospheric conditions. 4) The study explored feasible methods for reducing the health risks associated with WtE plants and provided specific recommendations for future MSW management and health risk assessment initiatives.

2. Material and methods

2.1 Study area

The Bohai Rim was selected as the research area, encompassing 44 cities across 5 provinces/municipalities (Tianjin, Hebei, Beijing, Shandong, and Liaoning), of which 30 cities had established WtE plants, as shown in **Figure 1**. The Bohai Rim had 96 WtE plants operating normally in 2020, collectively boasting a capacity of 9.98×10^4 t/d. In the Bohai Rim, moving grates and circulating fluidized beds were the dominant types of WtE incinerators, accounting for 93.4% and 6.6% of the total capacity, respectively. Compared to circulating fluidized bed incinerators, moving grate incinerators have demonstrated better performance in terms of durability and fly ash yield, making them more widely adopted at present.

Figure 1. The location of 96 WtE plants in the Bohai Rim in 2020. The base map was the 30' × 30' grid population density map, which was provided by Center for International Earth Science Information Network.

2.2 Emission Inventory

The emission inventory of WtE plants in 30 cities in the Bohai Rim included crucial information including WtE plants' locations, incinerator types, treatment capacities, and EFs for pollutants, such as SO_2, NO_X, cadmium + thallium (Cd + Tl), mercury (Hg), PCDD/Fs and chromium + cobalt + nickel + antimony + arsenic + lead + copper + manganese (Cr + Co + Ni + Sb + As + Pb + Cu + Mn). These data were obtained from continuous emission monitoring system (CEMS) networks developed by MEE. These networks provided daily real-time pollutant concentrations and detailed operation information of all the WtE plants in China, as seen in Supplementary Information (SI) Table S1. The pollutant emissions were calculated by Equations 1–3[14, 15]:

$$EF_{i,p} = \frac{1}{365}\sum_{t=1}^{365} C_{i,p,t} \times 4500 \times 1 \times 10^{-3} \quad (1)$$

$$M_{p,I} = N_{p,I} \times T \quad (2)$$

$$E_{i,p} = EF_{i,p} \times M_{p,I} \times 1 \times 10^{-6} \quad (3)$$

where: $E_{i,p}$ was pollutant *i*'s emission from plant p in 2020 (t/a); $EF_{i,p}$ was pollutant *i*'s EF of plant p in 2020 (g/t); $M_{p,I}$ was WtE plant p's MSW disposal quantity in 2020 (t/a); $C_{i,p,t}$ was pollutant i's concentration of plant p in the t day of 2020, $1 \le t \le 365$ (mg/m^3); $N_{p,I}$ was WtE plant p's capacity (t/d); 4500 was the theoretical flue gas rate (m^3/t); T was WtE plants' operation days per year (d/a), T was 330 d/a for moving gate incinerators and 300 d/a for circulating fluidized bed incinerators.

In addition, Oracle Crystal Ball was applied to calculate the uncertainty of $EF_{i,p}$ and $E_{i,p}$ of 96 WtE plants in the Bohai Rim. It was assumed that $N_{p,I}$ satisfied a normal distribution with a coefficient of variation (CV) of 10%[8]. Other parameters' distributions came from data fitting, the detailed information is shown in Table S2. Emission inventories' uncertainties were obtained through a 10000 Monte Carlo sampling process, as shown in Figure S1.

2.3 Health risk assessment

In this study, WRF was used to simulate the real meteorological field in the research area based on NCEP/NCAR reanalysis data, and the results were then used as the input meteorological field for CALPUFF. CALPUFF was applied to obtain the spatial distribution grid of air pollutants emitted by WtE plants in the atmosphere. Because the WRF/CALPUFF model required high computing conditions, January and July 2020 were chosen as the cold and warm periods of the year to run the model, respectively. The detailed settings of WRF and CALPUFF are shown in Text S1, Tables S3 and S4. The characteristics of the modeling result are shown in Table S5.

The HRA model was used to calculate the health risks of the WtE plants in the Bohai Rim and in 30 individual cities, based on each pollutant's inhalation exposure concentration output by WRF/CALPUFF. In order to reflect the impact of WtE plants' location on human health risks within the respective cities, we took into account the effects of spatial distribution of population when calculating HI and CR for each city. In this study, the research area was divided into 4 km × 4 km grids by CALPUFF (as shown in Text S1), and population-weighted HI and CR were used to indicate the non-carcinogenic risk and carcinogenic risk in the Bohai Rim and in each city, which were calculated by population-weighted average of HI and CR for all grids in the Bohai Rim as well as in each city, as shown in Equations 4–5:

$$\mathrm{HI} = \frac{\sum_m [\sum_i (C_{i,m,n} \times 10^{-3}/RfC_i) \times P_{m,n}]}{\sum_m P_{m,n}} \quad (4)$$

$$\mathrm{CR} = \frac{\sum_m [\sum_i (C_{i,m,n} \times \mathrm{SF}_i) \times P_{m,n}]}{\sum_m P_{m,n}} \quad (5)$$

where: *n* was the cities' code; *m* was the grid code in city *n*; $C_{i,m,n}$ was concentration of air pollutant i in grid m of city *n* generated from WRF/CALPUFF (μg/m^3), RfC was inhalation chronic reference concentration (mg/m^3), $P_{m,n}$ was the population in grid *m* of city *n* from Center for International Earth Science Information Network (https://sedac.uservoice.com/knowledgebase/topics/110829-gpwv4), SF_i was inhalation slope factor of pollutant *i* (μg/m^3)$^{-1}$.

The *RfC* and SF values were listed in Table S6.

2.4 Ridge regression model

The Ridge regression model was used to analyze the correlation between carcinogenic risk and non-carcinogenic risk of incineration and MSW components, the quantity of MSW incinerated, unit construction cost of WtE plants, and atmospheric diffusion conditions through SPSS 22.0 software.

Unit construction cost (yuan·d/t) was the investment quota of unit capacity, which reflects the technical level of local WtE plants to some extent. The dependent variables of Ridge regression model were the logarithms of CR and HI of incineration in each city in the Bohai Rim. The independent variables of Ridge regression model, which affected the health risks of local MSW incineration, were the logarithms of wind speed (m/s), temperature (K), rainfall (mm/month), the unit construction cost (yuan·d/t), and the annual quantity of 6 MSW components incinerated, such as paper (t/a), wood and straw (t/a), food waste (t/a), plastic and rubber (t/a), textile (t/a) and dust (t/a), in each city in the Bohai Rim.

Compared with multiple linear regression, Ridge regression analysis improved the least square method by giving up its unbias, and found the model equation with more realistic regression coefficients at the cost of losing some information. As the result, Ridge regression analysis can avoid the insignificance of parametric regression coefficients due to the presence of multicollinearity in the independent variables in the regression equation[33, 34].

Ridge regression analysis was used to explore the determinants of health risks of incineration and their correlations. The basic form of Ridge regression model was shown as Equations 6–7:

$$\mathrm{Ln(y)} = a_0 + \sum_{i=1}^{m} a_i \ln(\mathrm{n_i}) \quad (6)$$

$$a_i = (\mathrm{Ln(n_i)}^T \mathrm{Ln(n_i)} + \mathrm{K}I_P)^{-1} \ln(\mathrm{n_i})^T \mathrm{Ln(y)} \quad (7)$$

n_i was the i_{th} input variable. a_i was the regression coefficient, which can reflect the contribution of each independent variable to the dependent variable. I_P was the identity matrix of the same order as $\mathrm{Ln(n_i)}^T \mathrm{Ln(n_i)}$. K was a constant between 0 and 1, representing the artificial introduction error in the regression equation. The adjusted R^2 and regression equations were obtained by using stepwise backward elimination to remove independent variables that were not considered important.

In the analysis, the value of K should meet four conditions: (1) the ridge trace remains basically stable; (2) no unreasonable value for all regression coefficients; (3) all regression coefficients no longer have positive and negative fluctuations, and exhibit reasonable signs; (4) the sum of residual squares of ridge regression does not increase significantly compared to multiple linear regression.

In the regression model, the annual MSW disposal quantity of WtE plants in 30 cities can be calculated by the sum of all local WtE plants' $M_{p,I}$ (annual MSW disposal quantity of WtE plant *p*), which was calculated by Eq. 3. Table S7 lists the MSW disposal quantity of each city.

Through the review of 43 literature sources, we obtained 71 sets of data on the composition of MSW in different cities, and calculated the average values to represent the typical composition of MSW in each city, as displayed in Figure S2[35-71]. For the 12 cities where MSW component data could not be retrieved (Binzhou, Cangzhou, Chengde, Dezhou, Dongying, Hengshui, Jining, Rizhao, Weihai, and Xingtai), we utilized the average value of the MSW component data from adjacent cities to represent the typical composition of MSW in those cities.

The meteorological data for the 30 cities in the Bohai Rim were obtained from the Natural Environment Research Council (NERC) National Centre for Atmospheric Science of the United Kingdom (NCAS), which provided high-resolution grid data for wind speed, temperature, and rainfall in each of the 30 cities during January 2020 and July 2020. Using ArcGIS 10.5 software, we derived the wind speed, temperature, and rainfall data for each city in the Bohai Rim, as presented in Table S8.

3 Results and discussion

3.1 Health risks of WtE plants in the Bohai Rim

The HI of incineration in the Bohai Rim in January and July were 4.07×10^{-3} and 1.82×10^{-3}, respectively, both of which were below the acceptable threshold (HI < 1). Similarly, the CR of incineration in the Bohai Rim in January and July were 4.72×10^{-7} and 2.13×10^{-7}, both of which were also below the acceptable threshold ($CR < 1 \times 10^{-6}$). Notably, the health risks associated with WtE plants in the Bohai Rim were lower in July compared to January, suggesting that meteorological factors played a significant role in affecting the health risks of MSW incineration in the region. Specifically, the lower temperatures and slower wind speeds in January in the Bohai Rim hindered atmospheric circulation and the diffusion of pollutants, whereas the "semi-enclosed" topography and the intensified winter "downdraft" in the region further impeded the movement of air pollutants[14, 72, 73].

The order of pollutants' contribution to incineration's HI in the Bohai Rim was PCDD/Fs (35.45%) > SO_2 (25.58%) > NO_2 (22.83%) > Cr + Co + Ni + Sb + As + Pb + Cu + Mn (13.88%) > Cd + Tl (1.78%) > Hg (0.48%), while the order of pollutants' contribution to incineration's CR in the Bohai Rim was Cr + Co + Ni + Sb + As + Pb + Cu + Mn (71.6%) > PCDD/Fs (27.8%) > Cd + Tl (0.60%).

At the city level, due to the difference of MSW components, MSW disposal capacity, WtE plants' unit construction cost and meteorological conditions, the HI and CR of incineration varied widely among cities, as shown in Table 1. In January, the HI of the 30 cities varied from 7.29×10^{-4} to 1.40×10^{-2}, while the CR of the 30 cities varied from 1.19×10^{-7} to 9.81×10^{-7}. In July, the HI of the 30 cities varied from 6.64×10^{-4} to 8.68×10^{-3}, while the CR of the 30 cities varied from 6.22×10^{-8} to 5.74×10^{-7}. Shenyang and Beijing were the two cities with the highest health risk. Due to the more dense and larger incineration capacity, the HI in Shenyang and Beijing were 343.80% (January)–477.09% (July) and 159.90% (January)–202.97% (July) of the average HI in the Bohai Rim, while the CR in Shenyang and Beijing were 207.84% (January)–269.48% (July) and 158.69% (January)–351.64% (July) of the average CR in the Bohai Rim.

Table 1 HI and CR of 30 cities in the Bohai Rim

	HI	CR	HI	CR
	January		July	
Baoding	0.004759	7.31×10^{-7}	0.001573	2.56×10^{-7}
Beijing	0.006508	7.49×10^{-7}	0.003694	4.79×10^{-7}
Binzhou	0.003022	3.92×10^{-7}	0.001657	2.21×10^{-7}
Cangzhou	0.003585	5.09×10^{-7}	0.001256	1.88×10^{-7}
Chengde	0.000729	1.19×10^{-7}	0.001019	1.97×10^{-7}
Dalian	0.002831	2.55×10^{-7}	0.001048	1.36×10^{-7}
Dezhou	0.003564	4.29×10^{-7}	0.001874	1.80×10^{-7}
Dongying	0.002793	3.85×10^{-7}	0.001398	2.18×10^{-7}
Handan	0.002667	3.70×10^{-7}	0.000664	7.48×10^{-8}
Heze	0.004179	4.34×10^{-7}	0.001224	1.02×10^{-7}
Hengshui	0.003679	4.72×10^{-7}	0.001269	1.32×10^{-7}
Jinan	0.005971	5.98×10^{-7}	0.002113	2.04×10^{-7}
Jining	0.004439	4.89×10^{-7}	0.001321	1.32×10^{-7}
Langfang	0.004850	6.13×10^{-7}	0.002185	2.80×10^{-7}
Liaocheng	0.004084	4.56×10^{-7}	0.001888	1.75×10^{-7}
Linyi	0.003300	3.59×10^{-7}	0.001325	9.00×10^{-8}
Qinhuangdao	0.002028	3.70×10^{-7}	0.001052	2.56×10^{-7}
Qingdao	0.002829	3.51×10^{-7}	0.001059	1.33×10^{-7}
Rizhao	0.003465	4.18×10^{-7}	0.001177	1.28×10^{-7}
Shenyang	0.013952	9.81×10^{-7}	0.008683	5.74×10^{-7}
Shijiazhuang	0.004239	6.68×10^{-7}	0.001943	2.54×10^{-7}
Taian	0.004289	4.67×10^{-7}	0.001683	1.54×10^{-7}
Tangshan	0.002536	3.35×10^{-7}	0.001664	2.20×10^{-7}
Tianjin	0.005141	6.02×10^{-7}	0.002005	2.87×10^{-7}
Weihai	0.001753	2.22×10^{-7}	0.000993	1.26×10^{-7}
Xingtai	0.003527	4.85×10^{-7}	0.000992	1.18×10^{-7}
Yantai	0.001803	2.41×10^{-7}	0.001030	1.37×10^{-7}
Zaozhuang	0.003162	3.38×10^{-7}	0.000786	6.22×10^{-8}
Zibo	0.003480	4.40×10^{-7}	0.001217	1.83×10^{-7}
Weifang	0.003100	4.10×10^{-7}	0.001042	1.48×10^{-7}

3.2 Contributions of different MSW components on incineration health risks.

The average combustible and non-combustible components of MSW in Bohai Rim were 94.62% and 10.63%, respectively. Among the combustible MSW, the content of food waste was the highest in the Bohai Rim, accounting for 39.08% to 69.07%. It was followed by dust, plastic and rubber, paper, textile, and wood and straw, accounting for 1.24%–36.41%, 4.80%–19.82%, 3.80%–14.74%, 0.88%–5.90%, and 0.70%–5.57%, respectively (as shown in table S2). Food waste was widely distributed among MSW components in the Bohai Rim, and its high water content contributed to the relatively high water content of MSW in the Bohai Rim.

The contribution of each MSW component to Cd + Tl, Hg, SO_2, NOx, and Cr + Co + Ni + Sb + As + Pb + Cu + Mn was calculated as a percentage of its input quantity with respect to the total input quantity. The quantity of each MSW component incinerated in the Bohai Rim was determined from MSW composition and MSW disposal quantity of incineration (see Table S7). The concentration of pollutants in each MSW component in this study was calculated through the average of 49 sets of sampled data from 11 literature, as shown in Table S9. The contribution of each MSW component to PCDD/Fs was calculated as a percentage of its pollutant production with respect to the total pollutant production. Additionally, Thomas et al.[74] provided a method to calculate the EFs of PCDD/Fs through the contents of chlorine (Cl), Cu, and sulfur (S) in each MSW component.

As a result, the concentration of pollutants significantly varied in MSW components. Food waste, accounting for the largest portion (55.1%) of the total MSW, contained high levels of heavy metals. It had the highest concentrations of Cu and Pb, making it the primary source of heavy metal emissions from WtE plants. Moreover, food waste had the highest concentrations of S and nitrogen (N) among all MSW components, accounting for up to 0.49% and 3.86%, respectively, making it a critical raw material for the formation of NOx and SO_2 during the incineration process.

Because Cu on fly ash surfaces can catalyze PCDD/Fs formation[74, 75] and S had been identified as an inhibitor of PCDD/Fs formation[74, 76-78], dust with high Cu concentration and the lowest S content can lead to the formation of a large number of PCDD/Fs in the combustion process. Although food waste contained more copper and Cl than dust, it had a high content of S, so the contribution of food waste to the formation of PCDD/Fs was less than that of dust. Plastic and rubber had the highest concentration of Cl, accounting for 6.58%, which was mainly due to the high Cl content of PVC components in plastic and rubber. Therefore, plastic and rubber contained large amounts of Cl, which was considered to be a Cl source for the formation of PCDD/Fs[79, 80]. As a result, plastic and rubber, which accounted for 13.27% of MSW incinerated, contributed 22.40% to the PCDD/Fs emitted by WtE plants. In addition, textiles, with the highest concentrations of As, Ni, Cr, and Co among all MSW components, accounting for 2.98% of MSW incinerated, contributed 8.32% to the Cr + Co + Ni + Sb + As + Pb + Cu + Mn emitted by WtE plants.

The contributions of individual MSW components to the air pollutants emitted by WTE plants are shown in Figure 2.

Figure 2 Contributions of MSW components to pollutants emitted by WtE plants in the Bohai Rim. In 2020, a total of 0.174 t of Cd + Tl, 9.25 t of Cr + Co + Ni + Sb + As + Pb + Cu + Mn, 0.727 t of Hg, 3079.78 t of SO_2, 19019.50 t of NOx and 3.29 g-TEQ of PCDD/Fs were emitted from WtE plants.

Based on the analysis of the contribution of each pollutant to the health risks of incineration in the Bohai Rim, the relative contributions of MSW components to incineration's health risks were calculated and are shown in Figure 3a, b. Food waste was found to be the main contributor to SO_2, NO_2, and heavy metals, accounting for 56.91% of the total health risks (HI). Additionally, food waste was the primary contributor to CR, accounting for 57.83%, due to its high concentration of heavy metals. Textiles, although only comprising 2.98% of the MSW incinerated, contributed 6.98% of the incineration CR due to their high heavy metal content.

Figure 3. Contributions of MSW components to the health risks of incineration in the Bohai Rim. (a) and (b) indicated the contributions of MSW components to the HI and CR of incineration. The HI of incineration in the Bohai Rim in January and July was 4.07×10^{-3} and 1.82×10^{-3}, respectively. The CR of incineration in the Bohai Rim in January

and July was 4.72×10^{-7} and 2.13×10^{-7}, respectively. The conversion ratio of NO_2/NO_X is 0.75[81].

3.3 Performance of the Ridge regression model

The ridge trace diagram was obtained through ridge regression analysis, as shown in Figure 3. When K values were 0.5 and 0.6, the standardized regression coefficient of the independent variable tended to be stable.

When K value was 0.5 and 0.6, the ridge regression was carried out for ln (HI) and ln (CR), and the results showed that R^2 value was 0.654 and 0.613, respectively, indicating that the independent variables, such as wind speed (m/s), temperature (K), rainfall (mm/month), unit construction cost (yuan·year/ton), paper (ton/year), wood and straw (ton/year), textile (ton/year), food waste (ton/year), dust (ton/year), and plastic and rubber (ton/year) could explain 65.4% of the variation of HI and 61.3% of the variation of CR, as seen in Table 2. Through ANOVA test of the ridge regression model, it can be seen that the *P* value of the two regression results was less than 0.05, indicating that the model was significant. The detailed data of ANOVA test are shown in Table S10.

Table 2 Ridge regression analysis results

Parameter	Regression coefficient	
	HI	CR
K	0.5	0.6
Constant	15.274	5.922
Unit construction cost (yuan·a/t)	-0.127	-0.084
Wind speed (m/s)	-0.547	-0.286
Temperature (K)	-0.104	-0.101
Rainfall (mm/month)	-4.331	-4.089
Paper (t/a)	0.066	0.045
Wood and straw (t/a)	0.001	0.004
Textile (t/a)	0.046	0.026
Food waste (t/a)	0.114	0.061
Dust (t/a)	0.108	0.097
Plastic and rubber (t/a)	0.04	0.027
R^2	0.654	0.613
Adjusted R^2	0.561	0.509

The unit construction cost was negatively correlated with HI and CR. This meant that for WtE plants with the same capacity, the higher the investment, the lower the carcinogenic risk and non-carcinogenic risks caused by incineration. This was because that the higher investment was conducive to the implementation of more efficient clean incineration technology.

For meteorological conditions, wind speed, temperature, and rainfall were negatively correlated with HI and CR. This implies that when the wind speed, temperature, and rainfall increased, the air pollutants diffused and deposed more rapidly, consequently reducing the non-carcinogenic risk and carcinogenic risk caused by local WtE plants. In addition, the a_i of rainfall was much higher than those of temperature and wind speed, indicating that rainfall had the most efficient impact on health risks among these meteorological parameters. This was because the CALPUFF model was used to simulate the diffusion of pollutants emitted by WtE plants in this study, which can reflect the wet deposition of particulate and non-particulate pollutants, as well as the chemical reactions of NO_2 and SO_2[82-84]. Besides, wet deposition was an important mechanism for removing atmospheric pollutants, especially for Cu, Mn, Ni, Cr, and Pb, which were major contributors to incineration's health risks [85, 86].

For the MSW components, the quantity of paper, wood and straw, textile, food waste, dust, and plastic and rubber incinerated was positively correlated with HI, and the regression coefficients were 0.066, 0.001, 0.046, 0.114, 0.108, and 0.04, respectively. This indicated that the order of the influence degree of MSW components on non-carcinogenic risk caused by incineration was: food waste > dust > paper > textile > plastic and rubber > wood and straw.

The quantity of paper, wood and straw, textile, food waste, dust, and plastic and rubber incinerated was positively correlated with CR, and the regression coefficients were 0.045, 0.004, 0.026, 0.061, 0.097, and 0.027, respectively. This indicated that the order of the influence degree of MSW components on carcinogenic risk caused by incineration was: dust > food waste > paper > plastic and rubber > textile > wood and straw. Notably, food waste and dust contained more abundant Cl, N, and S compared to wood and straw, plastic and rubber, paper and textile, and heavy metals (Figure 3). These components had a great influence on the health risk of MSW incineration. Therefore, reducing the content of food waste and dust in feedstock can reduce the health risks caused by incineration in the Bohai Rim.

Among the six components of MSW in the Bohai Rim, wood and straw have the lowest coefficient. This is due to two main reasons. First, wood and straw make up a small fraction of the pollutants emitted by WtE plants in the Bohai Rim, as shown in Figure 3. Second, these components can reduce the production of fly ash and PCDD/Fs in incinerators[87]. Following the principles governing the generation of PCDD/Fs, fundamental elements, including carbon (C), hydrogen (H), and Cl, undergo synthesis within the temperature range of 200–400°C. Notably, within the incinerator's post-combustion area, the peak formation rate of PCDD/Fs occurs at temperatures between 300 and 325°C[88, 89]. Studies have shown that the addition of wood and straw to the incineration process can effectively reduce the weight loss of polyvinyl chloride (PVC) in the temperature range of 200 to 400 degrees Celsius. This, in turn, leads to a reduction in the production of PCDD/Fs[87]. Additionally, it is important to note that fly ash can act as a catalyst for the formation of PCDD/Fs[90]. In contrast, wood and straw, which are two of the six combustible components of MSW, have the lowest ash content[91]. Therefore, the lower ash content and associated properties of wood and straw make them less likely to pose health risks when incinerated.

3.4 Implication

Mandatory MSW classification is an effective measure to mitigate the emission factors of pollutants from WtE plants. By separating food waste, plastics, papers, textiles, and other materials, it becomes possible to recycle and treat them, using appropriate technologies, such as aerobic composting and anaerobic fermentation, to reduce the amount of waste sent to incinerators. This approach can significantly decrease the quantities of heavy metal-containing materials entering incinerators (e.g., waste batteries and electronic waste), thereby reducing the emissions of heavy metals, Cl, S, N, and other pollutants into the flue gas. This, in turn, minimizes the health risks associated with WtE plants[92, 93].

Due to the large variation in pollutants' concentration of each MSW component in the Bohai Rim, the effects of different MSW components' recovery on HI and CR of WtE plants in the Bohai Rim were significantly different. When the MSW recovery rate was 0–90%, the possible change of HI and CR was displayed based on the ridge regression model, as shown in Figure 4a and b.

Figure 4. The effects of different MSW components' recovery on HI and CR of WtE plants in the Bohai Rim (a) HI, (b) CR.

For the non-carcinogenic risk of incineration in the Bohai Rim, when the recovery rate was the same, food waste, dust, and paper's recovery had the most significant effect on the reduction of HI. When the recovery rate of food waste, dust, and paper was 40%, the HI was reduced by 5.66%, 5.37%, and 3.32%, respectively. For the carcinogenic risk of incineration in the Bohai Rim, when the recovery rate was the same, dust, food waste and paper's recovery had the most significant effect on the reduction of CR. When the recovery rate of dust, food waste, and paper was 50%, the CR was reduced by 6.50%, 4.14%, and 3.07%, respectively.

Assuming uniform recovery quality, the recovery of textiles from MSW in the Bohai Rim had the greatest potential to reduce HI and CR associated with incineration. This was followed by paper, dust, plastic, rubber, food waste, and finally wood and straw, in descending order of their impact on HI and CR reduction. A textile recovery volume of 1.44×10^6 tons (equivalent to 90% of the textile incinerated in the Bohai Rim) resulted in a significant reduction of 10.05% in HI and a corresponding decrease of 5.81% in CR. In contrast, a recovery quantity of 2.23×10^7 tons of food waste was required to achieve similar outcomes.

This phenomenon is primarily caused by the high levels of Cr, As, Ni, and Sb found in textiles[91, 94-101], as shown in Table S9. These heavy metals have relatively low reference concentrations (RfCs) (mg/m^3) and high slope factors (SFs) (m^3/ug), indicating a relatively high risk to human health, both in terms of cancer and non-cancer effects. Therefore, textiles have a higher health risk than other components of MSW.

In conclusion, the recovery of food waste proves to be the most effective way to mitigate the health risks associated with incineration. The recovery of textiles is also effective in reducing these risks. The classification of MSW can change the composition of the feedstock in incinerators, which can help reduce the negative health effects of pollutants emitted by WtE plants.

In addition to the above, the health risks of incineration (HI and CR) decrease with the increasing unit construction cost. The upgrade and optimization of clean incineration and ultra-low emission technologies can significantly reduce the health risks of incineration. For example, upgrading the "semi-dry + dry" deacidification process and incorporating wet scrubbers in WtE plants can effectively reduce the concentration of SO_2[102].

The ridge regression model revealed a significant impact of the unit construction cost on health risks, particularly on HI compared to CR, as seen in Figure S3. When the unit construction cost increases by 60,000 yuan·day/t, the HI decreases by 3.28% and the CR decreases by 2.18%. The development of more effective technologies for the removal of heavy metals and PCDD/Fs holds promise in mitigating these risks. On the other hand, reducing investment increases health risks, especially non-carcinogenic ones. This is because the unit construction cost of incinerators and purification facilities is limited by economic constraints.

Meteorological conditions also exert a significant impact on the dispersion and deposition of pollutants. Higher wind speed, rainfall, and temperatures are associated with lower health risks. Additionally, the height of the chimney affects the landing concentration of pollutants emitted by WtE plants. The simulation results show that taller chimneys improve pollutant dispersion, dilution, deposition, transformation, and decomposition, effectively reducing health risks, as seen in Figure S4. For example, increasing the chimney height from 80 m to 100 m reduces HI and CR by 41.28% and 33.19%, respectively. Further increasing the height to 200 m reduces HI by 21.47% and CR by 15.03%. Therefore, increasing the chimney height from 80 m to 100 m is an effective measure to mitigate the health risks associated with WtE plants.

4 Conclusions

Based on the emission inventory of WtE plants in the Bohai Rim in 2020, this study innovatively assessed the health risks from waste incineration by using ridge regression analysis. The study examined the correlation between health risks and potential influencing factors, and proposed specific measures to lessen the risks.

The conclusions are as follows:

(1) Incineration in 30 cities in the Bohai Rim had HI ranging from 7.29×10^{-4} to 1.40×10^{-2} in July and from 6.64×10^{-4} to 8.68×10^{-3} in January,. The CR ranged from 1.19×10^{-7} to 9.81×10^{-7} in July and from 6.22×10^{-8} to 5.74×10^{-7} in January. Both HI and CR were within acceptable limits (HI < 1, CR < 1×10^{-6}). However, HI and CR differed widely across cities.

(2) Ridge regression models for HI and CR had R^2 of 0.654 and 0.613, respectively, and were significant according to ANOVA tests. The regression coefficients for both models exhibited a negative relationship with unit construction cost, wind speed, temperature, and rainfall, and a positive relationship with quantities of various incinerated materials. MSW classification effectively reduced the health risks of incineration.

(3) When the recovery rate was constant, the recovery of food waste, dust, and paper had the most significant impact on reducing HI. In addition, dust, food waste, and paper had the most significant effect on reducing CR. When recovery quality was the same, textile recovery yielded the most substantial reduction in both HI and CR, followed by paper, dust, plastic and rubber, food waste, and wood and straw.

(4) Increasing the chimney height of WtE plants was found to accelerate the diffusion, deposition, transformation, and decomposition of air pollutants emitted by the plants. This led to a significant reduction in the health risks of incineration in the Bohai Rim, especially when the chimney was upgraded from the current height of 80 meters to 100 meters.

Author contributions

Z.S.H.: conceptualization, writing-original draft, data collection; J.C.C.: data collection, review & editing; A.B., Z.Y.L. and J.F.: conceptualization, review & editing; W.C.M.: conceptualization, writing–original draft, review & editing, supervision; Z.Y.Z.: data processing, software; Z.Q.: conceptualization, data processing, review & editing.

Declaration of competing interests

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.

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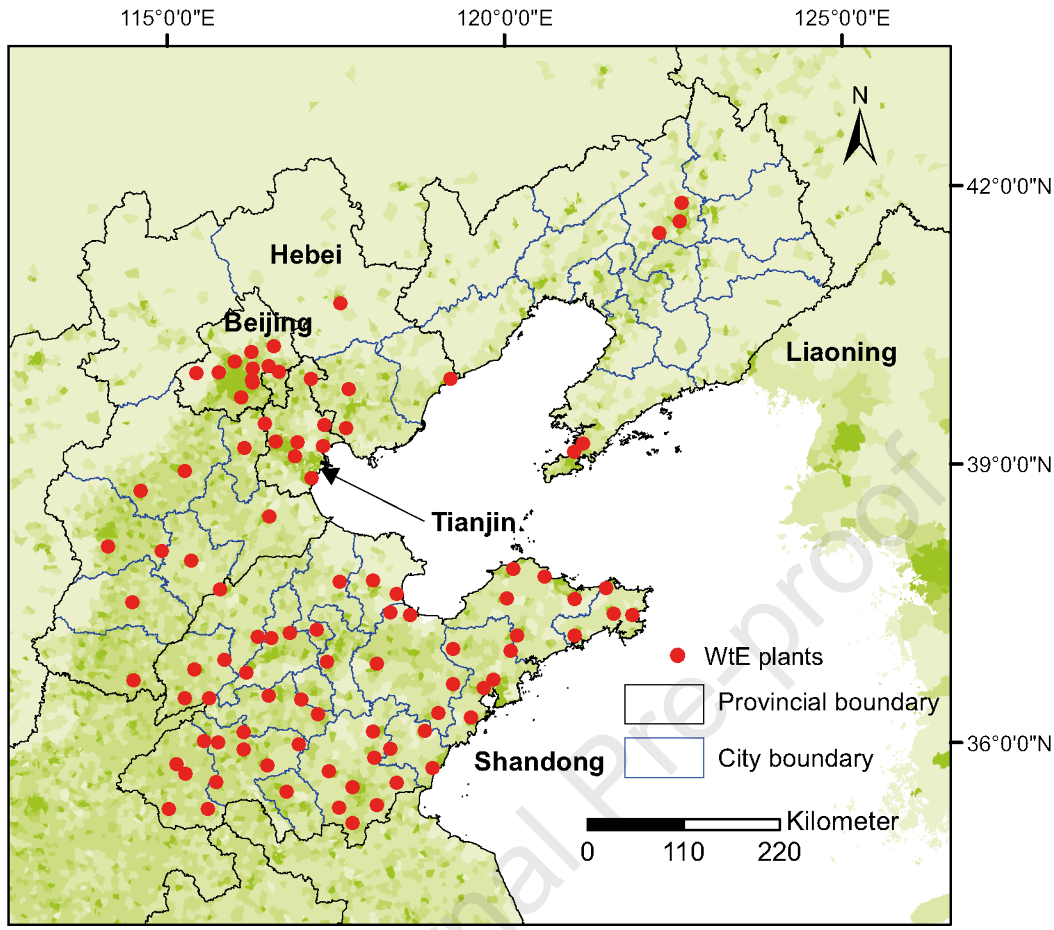
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City boundary
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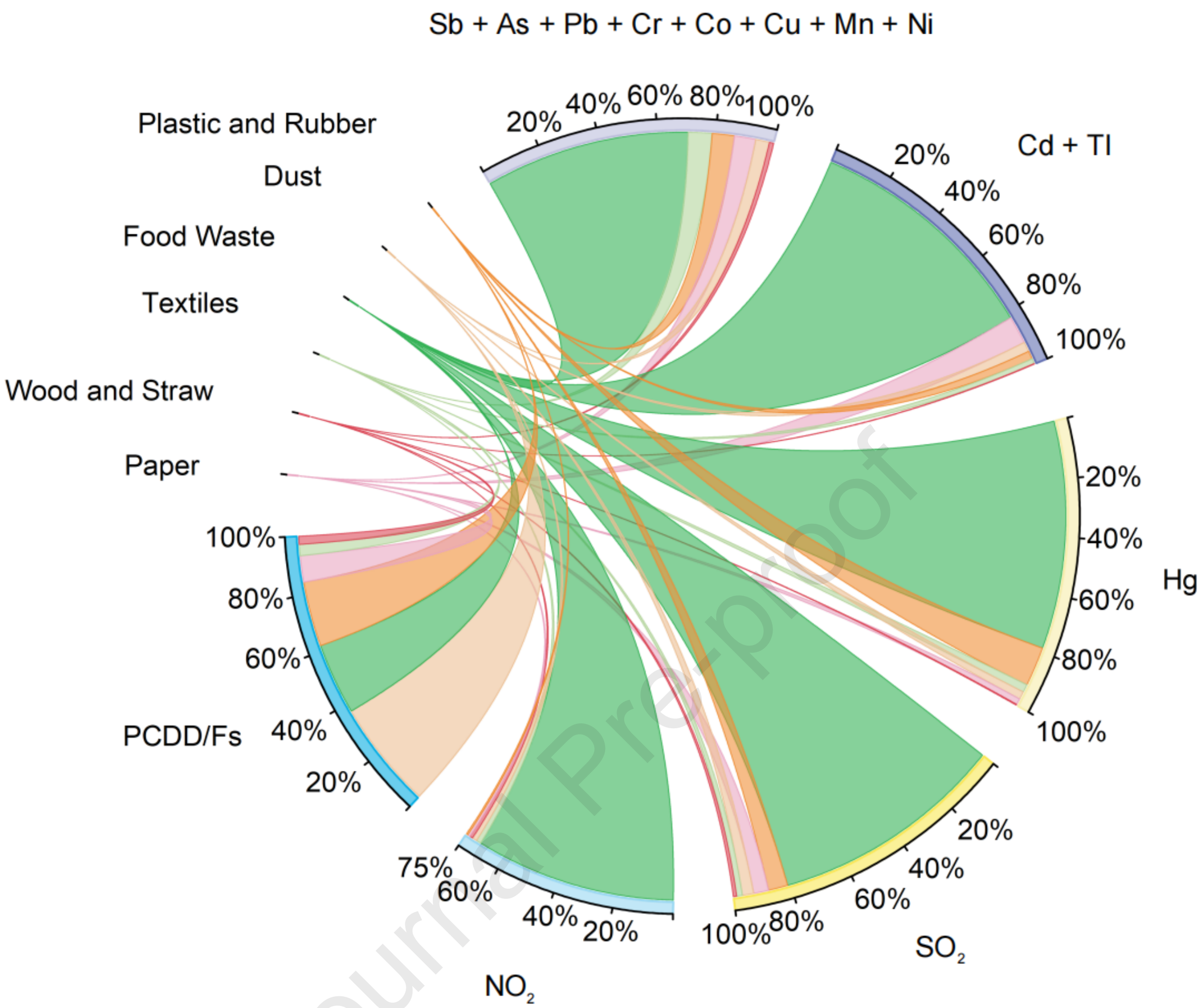
Sb + As + Pb + Cr + Co + Cu + Mn + Ni
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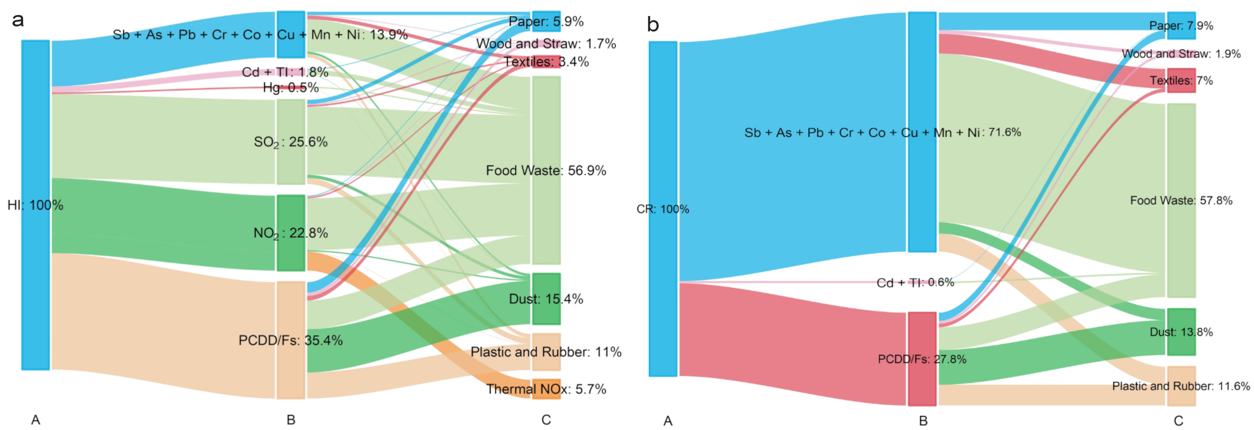
Dust
Food Waste
Textiles
Wood and Straw
Paper


a
HI: 100%
Sb + As + Pb + Cr + Co + Cu + Mn + Ni: 13.9%
Cd + Tl: 1.8%
Hg: 0.5%
SO_2: 25.6%
NO_2: 22.8%
PCDD/Fs: 35.4%
Paper: 5.9%
Wood and Straw: 1.7%
Textiles: 3.4%
Food Waste: 56.9%
Dust: 15.4%
Plastic and Rubber: 11%
Thermal NOx: 5.7%
A
B
C
b
CR: 100%
Sb + As + Pb + Cr + Co + Cu + Mn + Ni: 71.6%
Cd + Tl: 0.6%
PCDD/Fs: 27.8%
Paper: 7.9%
Wood and Straw: 1.9%
Textiles: 7%
Food Waste: 57.8%
Dust: 13.8%
Plastic and Rubber: 11.6%
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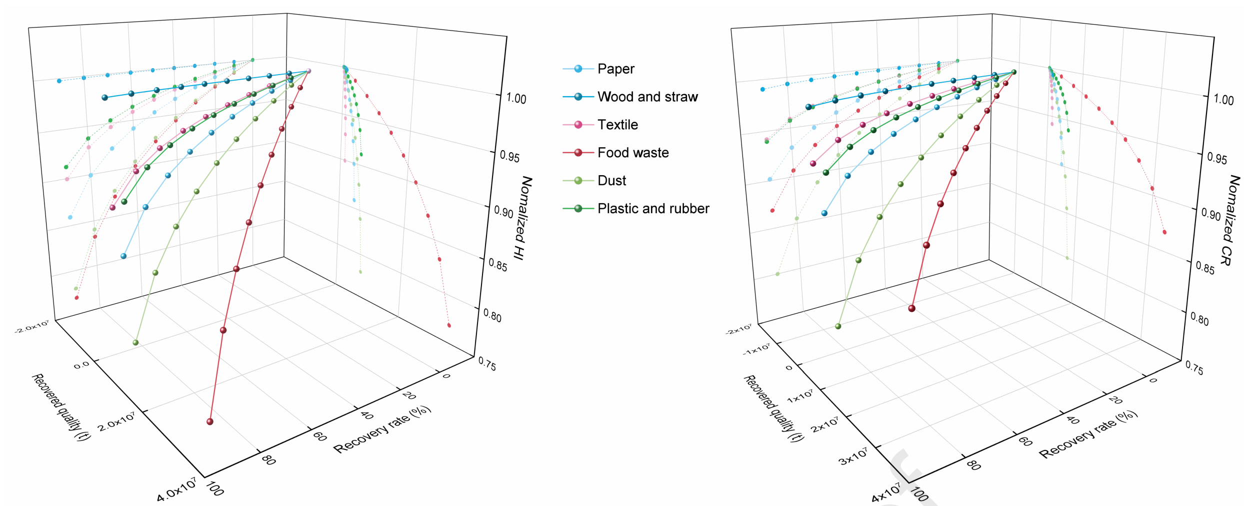
Paper
Wood and straw
Textile
Food waste
Dust
Plastic and rubber
Normalized HI
Normalized CR
Recovered quality (t)
Recovery rate (%)

Highlights

- Inhalation health risks from the Bohai Rim's WtE plants were evaluated.
- Determinants of incineration health risks and their correlations were investigated using ridge regression method.
- Hazard indices (HI) in January and July were 4.07×10^{-3} and 1.82×10^{-3}, respectively.
- Cancer risks (CR) in January and July were 4.72×10^{-7} and 2.13×10^{-7}, respectively.
- Health risks from WtE plants can be reduced through MSW classification.