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Research article

Insight into the formation of polychlorinated dibenzo-p-dioxins and dibenzofurans in hazardous waste incineration and incinerators: Formation process and reduction strategy

Fengyu He, Fei Wang^{*}, Yaqi Peng, Haibin Cui, Guojun Lv

Institute for Thermal Power Engineering, Zhejiang University, Hangzhou, 310027, China

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ABSTRACT

Incineration technology has been widely adopted to safely dispose of hazardous waste (HW). While the incineration process causes the formation of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs). Due to its extreme toxicity, many scholars have been committed to determining the PCDD/F formation process and reducing emissions in incinerators. Previous studies ignored the impact of incineration and fluctuation of feeding materials on PCDD/F formation in hazardous waste incinerators (HWIs). In this study, differences in PCDD/F formation between HWIs and municipal solid waste incinerators (MSWIs) were pointed out. The incineration section in HWIs should be carefully considered. Laboratory experiments, conventional analysis and thermogravimetry experiments were conducted. An obvious disparity of PCDD/F formation between 12 kinds of HWs was found. Distillation residue was found with remarkably higher PCDD/F concentrations (11.57 ng/g). Except for the Cl content, aromatic rings and C–O bond organics were also found with high correlation coefficients with PCDD/F concentrations (>0.92). And PCDD/Fs were formed through a chlorination process and structure formation process. All of these are helpful to further understand the PCDD/F formation process during HW incineration, optimize the operation conditions in HWIs and reduce the emission pressure of PCDD/Fs in the future.

1. Introduction

Accompanied with the rapid development of urbanization and industrialization, 248.69 million tons of municipal solid waste (MSW) and 86.53 million tons of hazardous waste (HW) were produced in 2021 in China (Yearbook, 2022).

Among all of these treatment methods, incineration technology has been widely adopted to dispose of MSW and HW, which has the advantages of volume reduction, energy recovery and detoxification (Lin et al., 2022). However, various pollutants, especially polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs), can be formed in incineration systems (Wang et al., 2014). PCDD/Fs have a long biological half-life, and exposure to PCDD/Fs can cause headache, infertility and cancer (Sharma et al., 2021).

Since the existence of PCDD/Fs in fly ash was found from municipal solid waste incinerators (MSWIs), many scholars have dedicated themselves to this field (Olie et al., 1977; Vehlow et al., 2006). Due to the

extreme toxicity of PCDD/Fs, the main purpose of scholars was to figure out the formation mechanisms in incinerators and reduce the emission of PCDD/Fs (Bo et al., 2022). After decades of efforts, including theoretical calculations (Pan et al., 2013), laboratory experiments (Soler et al., 2018), pilot-scale experiments (Lin et al., 2018) and full-scale experiments on MSWIs (Chen et al., 2019) and hazardous waste incinerators (HWIs) (Cao et al., 2018a), there has been some consensus on the extremely complex formation process of PCDD/Fs in academia.

Three main PCDD/F formation pathways were figured out: de novo synthesis (Stieglitz et al., 1997), precursors synthesis (Lomnicki and Dellinger, 2003), and chlorination of DD/DF (Tuppurainen et al., 2003). Two temperature zones were pointed out: low temperature heterogeneous catalytic reaction (200 °C–500 °C) and high temperature homogeneous reaction (500 °C–800 °C) (Zhang et al., 2017). Chlorination degrees and ratios of PCDD/PCDF were two important indicators of the chlorination process and formation pathways, respectively (Altarawneh et al., 2009).

In incinerators, the high temperature reaction was considered to be

E-mail address: wangfei@zju.edu.cn (F. Wang).

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^{*} Corresponding author. State Key Laboratory of Clean Energy Utilization, Institute of Thermal Power Engineering of Zhejiang University, Hangzhou, 310027, Zhejiang, China.

Nomenclature table		DSC	Differential scanning calorimetry				
		FTIR	Fourier Transform infrared spectroscopy				
PCDD/Fs Polychlo	rinated dibenzo-p-dioxins and polychlorinated	I-TEQ	International toxic equivalents				
dibenzof	irans	DD	Dibenzo-p-dioxins				
HW Hazardou	is waste	DF	Dibenzofurans				
MSW Municipa	l solid waste	CP	Chlorophenol				
HWIs Hazardou	is waste incinerators	PCA	Principal component analysis				
MSWIs Municipa	l solid waste incinerators	TCDD/F	s Tetrachlorinated dibenzo-p-dioxins and dibenzofurans				
APCDs Air pollu	APCDs Air pollution control devices		PeCDD/Fs Pentachlorinated dibenzo-p-dioxins and dibenzofurans				
SEM Scanning electron microscopy		HxCDD/Fs Hexachlorinated dibenzo-p-dioxins and dibenzofurans					
TG Thermogravimetry		HpCDD/Fs Heptachlorinated dibenzo-p-dioxins and dibenzofurans					
DTG Derivativ	e thermogravimetry	OCDD/H	s Octachlorinated dibenzo-p-dioxins and dibenzofurans				

well controlled with "3T + E" principles, which were high combustion Temperature (>1000 °C), long residence Time (>1s), high Reynolds number of Turbulence (>50,000) and Excess oxygen (McKay, 2002). This phenomenon was verified both in laboratories and incinerators (Zhan et al., 2016). Due to the participation of catalysts, the low-temperature formation process was greatly enhanced (Stieglitz, 1998). Thus, many existing studies have focused on the resynthesis of PCDD/Fs in low temperature (<500 °C) in air pollution control devices (APCDs) in addition to the PCDD/F emissions in stacks (Xia et al., 2022). PCDD/Fs characteristics and distributions in stack gas and fly ash have been figured out in MSWIs (Chen et al., 2018), and HWIs (Wang et al., 2014). Additionally, there were studies on PCDD/Fs inhibition by chemical inhibitors (Li et al., 2016).

However, studies about the detailed influence of incineration materials on PCDD/F formation were scarce in MSWIs and HWIs. For MSWIs, the MSWs had basic material components, which were mainly a mixture of fabrics, plastics, paper, kitchen residues, metal and glass from dustbins (He et al., 2022). While for HWIs, feeding HWs were identified based on harm to the environment, which could result in huge fluctuations in incineration characteristics (Wang et al., 2019). Although in incineration section, the principles of "3T + E" could effectively suppress PCDD/F formation, incineration products of some HWs were likely to produce abundant PCDD/Fs by reorganizing fragments.

The recent research also verified the necessity of focusing on the fluctuation of incineration materials in HWIs. Two individual experiments on the same stable HWI have found totally different emission characteristics and formation mechanisms of PCDD/Fs (He et al., 2022; Xiong et al., 2022). Precursors synthesis, especially chlorophenol route, was found to be dominant in the quench tower in HWIs, which was different from MSWIs (He et al., 2022). Scholars from Belgium also found the differences in PCDD/F formation between MSWIs and HWIs, and considered precursor synthesis as the dominant PCDD/F formation mechanism in some conditions in HWIs (Vermeulen et al., 2013). These anomalies were probably due to the impact of incineration materials, which was ignored in the former study, and will be discussed in Section 3.1.

There were many PCDD/Fs studies about MSWs in laboratories. A previous laboratory study adopted synthetic municipal solid waste (S-MSW) and burned it under a temperature gradient of 850, 600, 350 °C to simulate the formation of PCDD/Fs in MSWIs (Zhan et al., 2016). The mixture of S-MSW and coal was also burned in a lab-scale drop-tube furnace at 1300 °C and 800 °C (Lin et al., 2018). And scholars have studied the formation of PCDD/Fs by burning MSW at 800 °C in laboratory (Ma et al., 2018). While laboratory experiments focusing on the PCDD/F formation by different HWs were relatively lacking, and most PCDD/Fs studies about HW were full-scale HWIs experiments (Cao et al., 2018b; Li et al., 2017). The previous laboratory studies of HW samples were mainly focusing on combustion/pyrolysis parameters, kinetics, pollutants emissions and co-combustion processes (Zhang and Wang,

2022). While there existed few studies focusing on the relationships between PCDD/F formation and characteristics of HWs.

In this study, laboratory experiments for PCDD/F formation by the incineration of 12 different HW samples were conducted to reveal the PCDD/F formation characteristics in Section 3.2. Conventional analysis and Thermogravimetry analysis were conducted to figure out their characteristics. Principal component analysis (PCA) and correlation analysis were conducted to reveal the key variables that influence PCDD/F formation. Suggestions for lower PCDD/F emissions were given for HWIs based on this study. All of these are helpful to further understand the PCDD/F formation process during HWs incineration, optimize the operation conditions in HWIs and reduce the emission pressure of PCDD/Fs in the future.

2. Materials and methods

2.1. Materials

The typical HWI systems in China could be mainly divided into three sections (Fig. 1a). To evaluate the PCDD/F emission risk and incineration characteristics, 12 kinds of HWs were collected from the warehouse of feedings in an HWI in Zhejiang Province. The detailed information about the different types of HW samples were show in Table 1. And the microscopic and macroscopic morphologies of these samples were shown in Fig. S2. To better simulate site conditions, all the samples were ground to less than 150 μ m and tested under As-Received Basis. Proximate analysis and ultimate analysis were shown in Table 1. The Cl content was analyzed and determined by the Eschka fusion and titration method (GB/T 3558-2014).

2.2. Experiments of incineration

The systemic diagram of laboratory experiments was shown in Fig. S1. As the main apparatus, the 1.5m long tubular furnace consists of three sections with independent heaters and temperature controllers. Three sections were set at 850 °C, 600 °C and 350 °C respectively to simulate the incineration section, cooling section and APCDs section in real HWIs. Positioned in the quartz boat, 0.2g HW was completely incinerated with airflow (600 mL/min, 21% O₂ in N₂) in the incineration section. The test number of HW samples was shown in Table 1. Each test existed for 1 h to ensure complete combustion and PCDD/Fs adsorption. Before each test, three sections were stable at the set temperature, and the quartz boat was quickly pushed into the incineration section during startup.

2.3. Sampling, pretreatment, analyzing, quality assurance and quality control

For experiments of incineration, each experiment was conducted in duplicate. For Cl content analysis, each experiment was conducted in



Fig. 1. (a) Systemic diagram of three sections in typical HWIs in China (b) PCDD/F emission results of two individual experiments on the same HWI (c) Results of chlorination degrees and ratios of PCDD/PCDF on the same HWI (He et al., 2022; Xiong et al., 2022).

triplicate, following the Chinese national standard GB/T 3558-2014. For proximate analysis and ultimate analysis, each experiment was conducted in duplicate, following the Chinese national standard GB/T 30,732-2014 and GB/T 31,391-2015, respectively.

For the sampling process, XAD-2 resin in the glass chamber and toluene in the gas washer were connected with the incineration system through a silicone tube to adsorb the gas phase PCDD/Fs. Residue and quartz boats were also extracted to collect PCDD/Fs in ash. To avoid the effect of adsorption, toluene solutions were adopted to wash the silicone tube and glass pipe of the furnace. And toluene solution was added to the following pretreatment process.

For pretreatment, samples were first spiked with the ¹³C-labeled compound solution of PCDD/Fs, and Soxhlet extracted by toluene for 24h. Then the Soxhlet extract was concentrated into 1-2 ml and further cleaned by the multi-layer silica gel column and alumina column. Before analysis, the pretreatment procedure was completed by nitrogen flow and spiking with 0.5 ng of ¹³C-labeled recovery standards. All purified samples were analyzed by high-resolution gas chromatography coupled

with high-resolution mass spectrometry (HRGC/HRMS) (JMS-800D, JEOL, Japan). The procedures of PCDD/Fs samples were conducted according to EPA 23 method (Agency, 2017). The sampling and pretreatment processes were also described in detail in our previous research (Chen et al., 2008). The recoveries of all PCDD/Fs standards in samples range from 43.4% to 74.4%, achieving the requirement of EPA 23 method.

2.4. TG-DSC and TG-FTIR analysis

To study the detailed combustion process and characteristics of HW samples, TG experiments were adopted. Thermogravimetry (TG), Derivative Thermogravimetry (DTG) and Differential Scanning Calorimetry (DSC) tests were carried out by adopting a simultaneous thermal analyzer (TGA/DSC 3+, METTLER, Switzerland) at a heating rate of 25 °C/min in air atmosphere. HW samples (10 \pm 0.2 mg) were put into the alumina crucible and heated from 37 °C to 1000 °C with a flow rate of 50 mL/min.

Table 1

Proximate analysis, ultimate analysis and Cl analysis of HW samples.

Number	Type of HWs	M/%	A/%	V/%	FC/%	Q/(J/g)	C/%	H/%	N/%	S/%	O/%	Cl/%
HW1	Dust	8.79	25.89	57.58	7.74	14,123	33.97	4.81	4.66	0.72	21.16	0.023
		± 0.41	± 2.45	± 1.84	± 3.13	± 668	± 1.73	± 0.415	± 0.18	± 0.02	±0.79	± 0.005
HW2	Greasy filth	1.33	64.69	17.6	16.38	26,842	16.38	2.18	0.07	0.14	15.21	0.069
		± 0.11	± 0.41	± 0.32	± 0.61	± 718	± 0.60	± 0.07	± 0.01	± 0.03	± 0.93	± 0.006
HW3	Industrial sludge	0.82	23.99	61.78	13.41	24,006	55.71	4.92	2.11	5.5	6.95	0.292
		± 0.26	± 0.68	± 0.08	± 0.96	± 227	± 0.82	± 0.12	± 0.065	± 2.1	± 2.27	± 0.007
HW4	Distillation residue	16.17	0.46	82.94	0.43	16,376	43.79	3.98	0.84	2.29	32.47	14.26
		± 0.63	± 0.08	± 0.76	± 0.02	± 259	± 1.54	± 0.14	± 0.065	± 0.09	± 0.35	± 0.004
HW5	Filter residue	21.49	68.49	9.53	0.49	1017	1.2	2.73	0.09	0.02	5.98	3.77
		± 0.74	± 1.75	± 0.24	± 0.07	± 85	± 0.11	± 0.12	± 0.01	± 0.0	± 1.75	± 0.007
HW6	Lacquer residue	1.26	13.71	82.05	2.98	24,754	53.75	6.62	5.7	0.76	18.2	0.201
		± 0.005	± 0.66	± 0.125	± 0.79	± 203	± 0.645	± 0.07	± 0.12	± 0.24	± 0.31	± 0.002
HW7	Factory sludge	2.1	24.22	62.21	11.47	23,658	53.18	4.89	2.25	1.33	12.03	0.708
		± 0.835	± 0.134	± 0.75	± 0.69	± 360	± 0.76	± 0.43	± 0.06	± 0.02	± 0.17	± 0.009
HW8	Waste powder	0.95	0.8	72.64	25.61	26,903	26.68	3.65	0.01	18.02	49.89	0.060
		± 0.05	± 0.03	± 0.85	± 0.47	± 489	± 0.74	± 0.13	± 0.00	± 0.79	± 2.67	± 0.003
HW9	Wastewater treatment sludge	6.92	43.17	49.1	0.81	5791	20.41	2.04	2.56	0.33	24.57	0.815
		± 0.74	± 1.51	± 1.67	± 0.04	± 103	± 0.41	± 0.09	± 0.07	± 0.025	± 1.54	± 0.007
HW10	Oily sludge	29.49	41.21	22.11	7.19	3246	9.56	1.15	0.07	0.98	17.54	0.027
		± 3.57	± 7.64	± 1.54	± 0.68	± 354	± 1.01	± 034	± 0.03	± 0.13	± 3.31	± 0.009
HW11	Pigment sludge	3.4	69.72	25.21	1.67	6268	16.23	1.09	3.1	0.28	6.18	13.03
		± 1.01	± 8.64	± 6.1	± 0.58	± 1172	± 3.81	± 0.18	± 1.1	± 0.11	± 1.39	± 0.017
HW12	Waste activated carbon	2.29	2.32	26.32	69.07	26,989	73.75	1.9	4.3	2.29	13.15	0.026
		± 0.55	± 0.23	± 2.63	± 1.69	± 566	± 4.23	± 0.04	± 0.14	± 0.07	± 0.02	± 0.006

To further study the pollutant emissions during the combustion, the Fourier Transform Infrared Spectroscopy (FTIR) (BRUKER Tensor 27) coupled with TG analyzer (NETZSCH STA 449 F3 Jupiter) was adopted. To avoid gas condensation, the gas pipeline connecting TG and FTIR was heated and maintained at 220 °C. And gases evolved from combustion traveled through the flow cell continuously. FTIR Spectra in the range of 4000 cm⁻¹–650 cm⁻¹ IR absorption bands were collected with 2 cm⁻¹ resolution by heating 10 mg HW samples to 1000 °C in air atmosphere. Before the TG-FTIR test, the background signal was collected and subtracted.

2.5. Statistical analysis and principal component analysis

In the PCDD/Fs experiment, 17 toxic tetra-PCDD/Fs to octa-PCDD/Fs congeners were separated and analyzed. For 17 congeners, international toxic equivalents (I-TEQ) were employed based on the toxic equivalency factors (VandenBerg et al., 1998; Xia et al., 2023), and the total TEQ values of the 17 toxic PCDD/F congeners were calculated as:

$$C_{TEQ} = \sum C_i \times TEQ$$

 C_i , the concentration of each PCDD/Fs congener; TEQ_i , the TEQ value of each PCDD/Fs congener; C_{TEQ} , the total TEQ value of each sample.

Chlorination degrees of PCDD/Fs were calculated as:

Chlorination degree =
$$\frac{\sum C_i \times n_i}{C}$$

 C_i , the concentration of each PCDD/Fs congener; n_i , the number of substituted chlorines in each PCDD/Fs congener; C, the overall concentration of PCDD/Fs congeners.

In order to better study the characteristics of HW samples, scanning electron microscopy (SEM, Sigma300, ZEISS, Germany) was adopted to analyze the surface morphology of various HWs. Moreover, to analyze the relationships between PCDD/F emissions and comprehensive characteristics of HWs and figure out the crucial variables, correlation analysis and principal component analysis (PCA) were applied using SPSS 24 software, based on the PCDD/Fs concentrations, I-TEQ values, proximate analysis, ultimate analysis, Cl contents analysis, DSC characteristics and FTIR peaks of pollutants absorption.

3. Results and discussion

3.1. Formation of PCDD/Fs in HWIs and comparison between HWIs and MSWIs

As shown in Fig. 1, two individual full-scale experiments on the same HWI have found remarkably different emission results and PCDD/F formation characteristics. A relatively high PCDD/F emission level was pointed out in experiment A (0.13 ng I-TEQ/Nm³), which exceeded the European emission standards (He et al., 2022). As mentioned above, chlorination degrees and ratios of PCDD/PCDF were two important indicators of the chlorination process and PCDD/F formation pathways (Altarawneh et al., 2009). In experiment A, a dominance of PCDDs and high chlorination degrees in flue gas, stack gas and quench tower ash were found, which originated from chlorophenol route synthesis (He et al., 2022). While emission results of experiment B were remarkably different from that of experiment A (Xiong et al., 2022). Similar to those in typical MWSIs, PCDFs and de novo synthesis were dominant in experiment B, and a lower PCDD/F emission level (0.043 ng I-TEQ/Nm³) was found.

Although it was not possible for the operation conditions to be completely the same. But the basic conditions, such as feeding rate, temperature distributions and rate of activated carbon injection (listed in Table S1), were similar during two individual experiments. And the cooling section and APCDs section in the same HWI system were operated stably in both experiments. Thus the incineration materials could be the main reason for the different PCDD/F emission results. Interestingly, feeding hazardous waste was found different in the two experiments, as shown in Fig. 1b. Chlorine content in HWs was high in experiment A (10.3%), while HWs in experiment B were found with lower chlorine (5.26%) and high sulfur (2.82%). This figured out that even for the same HWI, the PCDD/F formation and emission characteristics could be totally different due to the fluctuation of feeding materials into the furnace at different times.

The results also indicated a large difference of PCDD/Fs research between HWIs and MSWIs. As mentioned above, the cooling section and APCDs section were carefully concerned by scholars in MSWIs (Chen et al., 2018). Because PCDD/Fs was mainly formed in cooling section, and APCDs section could significantly diminish gas-phase PCDD/Fs and pollutants by adopting activated carbon (Hajizadeh et al., 2011). MSWs with a basic component list were relatively stable, which indicated less influence from the feeding materials in incineration section on PCDD/F formation. HWs were mainly identified due to their harm to the environment, not the material components or incineration characteristics (Wang et al., 2019). From this perspective, the incineration section, as resources of PCDD/F formation, played the key role and should be firstly concerned in HWIs.

The literature also seemed to support this viewpoint. Fig. 2, Table S2 and Table S3 summarized the comparison of chlorination degrees and PCDDs/PCDFs ratios in flue gas and fly ash between 2 HWIs with high chlorine and 4 classical MSWIs (Chen et al., 2019; He et al., 2022; Ma et al., 2021; Wang et al., 2019).

Obviously, all the values of chlorination degrees collected from HWIs samples were higher than those from MSWIs samples. A similar phenomenon was also observed in ash samples. The high chlorine content in feeding HWs enhanced the risks of over-chlorination and excessive PCDD/F emission.

For PCDD/PCDF ratios, PCDFs dominated in 3 MSWIs, which was the typical distributions of PCDD/Fs congeners, and de novo synthesis was the main mechanism (Chen et al., 2019). While the dominance of PCDDs was observed in quench tower ash and flue gas samples in HWI A. All the stack gas and ash samples from HWI B were identified with PCDDs as the main products, indicating precursors as the main formation synthesis in this HWI (Wang et al., 2019). In flue gas samples of HWI B, PCDFs was the main products. Due to higher values of Cl content and fluctuation of characteristics, the PCDD/F formation process in HWIs was more

complex. The previous full-scale study also found a remarkable difference in PCDD/F formation between MSWIs and HWIs (Vermeulen et al., 2013). All of these call for more PCDD/F-related research on the incineration of HW materials.

3.2. PCDD/F formation from different hazardous wastes by laboratory experiments

As discussed above, deeper research on PCDD/F formation by different HWs was required, which could be helpful for guiding the operation of HWIs to reduce PCDD/F emission pressure.

Therefore, laboratory experiments were conducted, as shown in Fig. S1 and Fig. S2. 12 kinds of HW samples were collected from the warehouse of an HWI in Zhejiang Province, with different categories according to National Hazardous Waste List of China. The proximate, ultimate and Cl content analysis were shown in Table 1. The PCDD/Fs concentrations, chlorination degrees and distributions in different samples were shown in Fig. 3. It is worth mentioning that both the PCDDs and PCDFs were mostly formed at high temperatures in the laboratory experiments, because there existed few mediums for heterogeneous synthesis (Xu et al., 2018).

Obviously, under stable laboratory conditions, PCDD/Fs concentrations formed by most HW samples were controlled at low levels (<1 ng/ g). This phenomenon was consistent with the previous study. Existing studies have shown that the formation of PCDD/Fs in the incineration



Fig. 2. (a) Comparison of chlorination degrees in flue gas between HWIs with high Cl and classical MSWIs (b) Chlorination degrees in fly ash (c) Comparison of PCDDs/PCDFs ratios in flue gas between HWIs with high Cl and classical MSWIs (d) PCDDs/PCDFs ratios in fly ash.



Fig. 3. (a) PCDD/F formation concentrations of different HW samples (b) Chlorination degrees and ratios of PCDD/PCDF (c) Distributions of PCDD/Fs congeners.

section was quite limited under good operation conditions in incinerators (Everaert and Baeyens, 2002).

However, distillation residue (HW4) in the HW samples showed prominent PCDD/F formation ability. A total of 11.57 ng/g PCDD/Fs was formed by distillation residue, which was one order of magnitude higher than concentrations in other samples. Some HW samples (HW3, HW5) also formed more PCDD/Fs. And there existed a remarkable difference in PCDD/F formation. For HWIs, the feeding materials were mixed according to the HWs received in the waste pool and then incinerated in the furnace. When specific HWs such as distillation residue were received and incinerated in HWIs without pertinent control measures, there could be a sharp rise in PCDD/F formation (Wang et al., 2014). And APCDs sections would struggle to control PCDD/F emissions. This further ensures the necessity of this study.

For chlorination degrees of PCDD/Fs, HW4 and HW11 were identified with the highest Cl content (Table 1), while the chlorination degrees were not obviously higher, as shown in Fig. 3b. Chlorination degrees of PCDDs were stably higher than those of PCDFs, consistent with our previous study (Lu et al., 2021). Due to the dominance of OCDD (Fig. 3c), HW3 and HW9 were identified with highest values of chlorination degrees. PCDD/Fs concentration formed by HW11 with high Cl was at average levels. Such a phenomenon indicated that there might exist other factors that affected PCDD/F formation except for absolute Cl content in HWs. It could be inaccurate to determine the PCDD/F formation risk in HW samples by a single Cl content indicator.

For PCDD/PCDF ratios, PCDDs and PCDFs separately dominated (>50%) in 6 HW samples, indicating the complexity of PCDD/F formation from HW incineration. OCDD was the main product for most HW samples. While for distillation residue (HW4), OCDF, 1234678-HpCDF and 2378-TCDF were dominant. Differences in distributions and concentrations resulted from the difference in characteristics between HW samples. To further figure out the characteristics and explain the PCDD/ F formation results, TG-DSC, TG-FTIR and PCA were required.

3.3. Relationships between PCDD/F formation and characteristics of HW samples

3.3.1. Combustion characteristics of HW samples

To figure out the incineration characteristics of HW samples, TG-DTG-DSC experiments were conducted, as shown in Fig. 4. The proximate analysis, ultimate analysis and Cl content analysis (GB/T 3558-2014) of HW samples were shown in Table 1. It is worth mentioning that the proximate analysis results of HW2 were consummated by TG experiments due to the weight increase after incineration.

For most HW samples (1, 3, 6, 7, 8, 10 and 12), the incineration processes were stable and similar to the incineration of typical coal fuel (Fig. S3). The weights of samples dropped rapidly at 400–600 $^{\circ}$ C, accompanied by the weight loss peak of the DTG curve and the exothermic peak of the DSC curve. This could result from the

combustion of fixed carbon, which plays as an important source of calorific value (Zhang et al., 2021).

While for distillation residue (HW4), nearly no DTG peaks were observed from 400 to 600 °C. The first endothermic peak of the DSC curve originated from the evaporation of moisture at 100 °C (Zhang and Wang, 2022). When the temperature rose to nearly 200 °C, the weight of distillation was rapidly reduced by 80%, accompanied by a DSC endothermic peak. The high volatile content (82.94%) in HW4 could probably be the key reason for its prominent PCDD/F formation ability.

TG experiments also showed that some HW samples were not suitable for calorific value utilization in HWIs. The weight of greasy filth (HW2) decreased by 28% before 220 °C with evaporation and volatilization, and then rose due to the reaction between ash and air. Few combustions of fixed carbon between 400 and 600 °C were observed in HW5, HW9 and HW11, which contributed very limited calorific value. And high ash content in HWs could hinder the stable operation of HWIs (Greenwood and Geisenhoff, 2003).



Fig. 4. TG-DTG-DSC experiments of different HW samples.

3.3.2. Pollutant emission characteristics of HW samples during combustion

To further figure out the gaseous products from the incineration of HW samples, TG-FTIR experiments were conducted. The FTIR spectral bands of related gaseous products and functional groups were collected based on the FTIR bands of similar samples from the previous literature, as shown in Table 2 (Chen et al., 2015, 2020; Hinedi et al., 1993). The relationship of wavenumbers and absorption peaks as 2D diagrams was shown in Fig. S4.

As shown in 3D diagrams in Figs. 5, 4 main kinds of organic components were found: stretching vibration of C-H, C-C, C-O bonds and C-C stretching vibration of aromatic rings. CO2 peaks caused by the combustion of fixed carbon dominated from 400 to 600 $^\circ C$ for most HWs samples, coinciding with the exothermic peak of DSC as shown in Fig. 4 (Zhang and Wang, 2022). For greasy filth (HW2), volatile organics of C–H bond were the main product at 200 °C. Considering that there were no other organic peaks, CH₄ was the product. Emission of SO₂ was observed at 250 °C due to the high content of sulfur in HW8. A slight emission of C-C organics was observed for pigment sludge (HW11) and waste activated carbon (HW12). Emissions of HCl were limited, indicating that chlorine mainly remained in the slag as salts or volatilized as organics (Tang et al., 2022). Distillation residue (HW4) was identified with high carbon content (43.79%, Table 1), while few emissions of CO₂ were observed in the TG-FTIR experiment. And various organics were found when the temperature reached 200 °C. C–H bond was found in the FTIR band. C-C stretching vibration of aromatic rings and C-O bonds were also found, indicating that the volatile organics of HW4 were composed of C-H, C-O and aromatic rings.

3.3.3. PCA, correlation analysis and PCDD/F formation process during incineration

To further analyze relationships between PCDD/F formation and characteristics of HWs samples and figure out the crucial variables, principal component analysis (PCA) and correlation analysis were applied using SPSS 24 software.

Based on the experimental data and analysis results above, the PCA and correlation analysis selected PCDD/Fs concentration, I-TEQ value, ratio of PCDD/PCDF, chlorination degree (PCDD/Fs experiments), proximate analysis, ultimate analysis, Cl content analysis (conventional characteristics), DSC exothermic peaks value, CO₂ peaks, SO₂ peaks, C–H bond peaks, aromatic rings peaks, C–O peaks and C–C peaks values (TG-DSC & TG-FTIR experiments) as the variables. And the analysis results were shown in Fig. 6. The analysis data was shown in Table S4. The rotated component matrix converged after 7 iterations. Due to the complexity of data, 4 factors were isolated by PCA, which together explained 80.04% of the total variance, meeting the typical threshold of 80%, and explained 29.6%, 22.9%, 16.0% and 11.5% from 1 to 4, respectively. The factor scores of variables were shown in Table S5.

To better visualize the PCA results, 3 main factors were selected to draw 3D loading plot, as shown in Fig. 6a. Obviously, two groups with PCDD/Fs variables as the core were found. In group A, PCDFs, concentrations, I-TEQ (PCDD/Fs variables) and FTIR peaks of aromatic rings and C–O were closely distributed in the lower right corner. PCDDs and Cl content analysis were also distributed nearby. This showed that in the

Table 2

Summary of FTIR absorption bands selected for analysis of main gaseous products and functional groups (Chen et al., 2015, 2020; Hinedi et al., 1993; Zhang and Wang, 2022).

Gaseous products/functional groups	Wavenumber of peaks (cm $^{-1}$)				
CO ₂	2360 & 670				
SO ₂	1375				
HCl	2798				
C–H stretching vibration/CH ₄	2935				
C–C/C==C stretching vibration	1530				
C-C stretching vibration of Aromatic rings/Benzene	1490				
C–O/C–O–C stretching vibration	1220				

incineration process of HWs, these indicators were closely related (Wang et al., 2020). Compared to Cl content analysis, aromatic rings and C–O peaks in TG-FTIR analysis could better reflect the PCDD/F formation ability of HW samples.

Meanwhile, chlorination degrees of PCDD/Fs (Cl-PCDD/Fs) and ratios of PCDD/PCDF were distributed in group B, accompanied by calorific values, CO_2 peaks, DSC peaks and element C, H, N analysis. Due to the stably higher Cl-PCDD/Fs values of PCDDs than that of PCDFs as discussed above, the ratio of PCDD/PCDF was related to Cl-PCDD/Fs. The PCA loading plot of 2 main factors also found similar results, as shown in Fig. 6b. The separation of PCDD/Fs indicators into two groups showed that the PCDD/F formation process by HWs incineration could be mainly divided into 2 independent processes: chlorination process and structure formation process, which will be discussed later and shown in Fig. 6d.

To better quantify the relationship between variables, the correlation matrix was calculated. The correlation plot was shown in Fig. 6c, and the correlation matrix was shown in Table S6. The calorific value was negatively correlated with ash (-0.599) and moisture (-0.744), and positively correlated with fixed carbon (0.554), volatile (0.455), CO₂ peak of FTIR (0.493) and DSC peak (0.463). SO₂ peaks of FITR were also positively correlated with element S (0.945) and O (0.813) in the ultimate analysis. This showed that TG-experiments were well verified with conventional analysis.

Consistent with PCA, the PCDD/Fs indicators were divided into two groups with high correlation coefficients. The correlation between concentration and Cl-PCDD/Fs was weak (-0.249). Three indicators (Cl content, C–O bond, aromatic rings) were found correlated with PCDD/Fs concentrations and I-TEQ values. The Cl content was correlated with PCDD/Fs concentration (0.689) and I-TEQ values (0.699), while C–O peaks and aromatic rings peaks showed obviously higher coefficients (>0.92).

For Cl-PCDD/Fs and ratios of PCDD/PCDF, no highly correlated indicators were found. Element C and DSC peaks were correlated with Cl-PCDD/Fs (0.484) and PCDD/PCDF (0.467), respectively. Interestingly, the correlation between Cl-PCDD/Fs and Cl was weak (-0.327), which indicated that Cl influenced PCDD/Fs concentrations more than chlorination degrees.

The results of PCA and correlation analysis could also be verified by analyzing the formation process of PCDD/Fs, as shown in Fig. 6d. Structurally, PCDD/Fs are formed by the connection of two aromatic rings, with C–O bond (PCDDs) or C–C bond (PCDFs) as the bridge (Tang et al., 2022). In previous studies, Precursors route, De novo synthesis and chlorination of DD/DF were considered the main PCDD/F formation mechanisms (Ma et al., 2021). De novo synthesis was not the main mechanism during HWs incineration due to the lack of conditions (low temperature, heterogeneity and catalysts) as mentioned above (Wielgosinski et al., 2016). In the precursors route, PCDD/Fs were formed by condensation or rearrangement of precursors, and PCDD/Fs could also be generated with Cl substituted on DD/DF at 2,3,7,8 (Chen et al., 2019).

Both the precursors route and chlorination of DD/DF could occur with the participation of C–O bond organics and aromatic rings (Fig. 6d). For structure formation, few organic fragments could be released after incineration (Zhuang et al., 2022). And DD/DF could be formed from the reaction of C–O organics and aromatic rings, then toxic PCDD/Fs was generated with chlorination process (Tuppurainen et al., 2003). Some previous studies regarded precursor synthesis as the main mechanism in HWIs (Vermeulen et al., 2013; Wang et al., 2019). In this way, precursors such as chlorobenzene and chlorophenol were formed by the reaction of aromatic rings, C–O organics and chlorine sources, then the structure formation process was completed by condensation or rearrangement of precursors (Pan et al., 2013). Combined with the former discussions of PCA, structure formation process seemed to be the key factor that influenced the concentration and I-TEQ values of PCDD/Fs. Chlorination process was more complex, and could be related



Fig. 5. 3D diagrams of TG-FTIR experiments of different HW samples.

to the incineration conditions based on the PCA and correlation analysis.

4. Conclusions

In this study, differences in PCDD/F formation between HWIs and MSWIs were pointed out. By laboratory experiments of PCDD/Fs, conventional analysis and TG-DSC & TG-FITR, the comprehensive characteristics of different HW samples were figured out. PCA and correlation analysis were conducted to analyze the relationships between variables and PCDD/F formation. The conclusions and suggestions to HWIs were as follows:

- (1) The incineration section in HWIs deserved more attention in terms of PCDD/F formation except for the cooling section, APCDs and stack that scholars have already focused on.
- (2) An obvious disparity of PCDD/F formation between different HW samples was found. By avoiding specific HWs such as distillation residue into the feeding materials, the risk of PCDD/F emissions from HWIs could be reduced remarkably.
- (3) Aromatic rings and C–O bond organics were found the key organic components during HWs incineration, and PCDD/Fs was formed by chlorination process and structure formation process.

Moreover, the following laboratory experiments and pilot sacle experiments were conducted in progress, in order to deeply understand the



Fig. 6. (a) 3D PCA loading plot results of 3 factors (b) PCA loading plot results of 2 factors (c) Correlation coefficients analysis of variables (d) Formation of PCDD/Fs by HW incineration.

PCDD/F formation mechanisms in HWIs, figuring out effective control methods, and verify the existing findings, as shown in Fig. S5. All of these are helpful to further understand the PCDD/F formation process during HWs incineration, optimize the operation conditions in HWIs and reduce the emission pressure of PCDD/Fs in the future.

Credit authorship contribution statement

Fengyu He: Formal analysis, Investigation, Conceptualization, Methodology, Software, Validation, Writing- original draft, Visualization, Data curation, Writing-review & editing. Fei Wang: Funding acquisition, Writing-review & editing, Supervision. Yaqi Peng: Writingreview & editing, Project administration, Formal analysis. Haibin Cui: Supervision. Guojun Lv: 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

Data will be made available on request.

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Appendix A. Supplementary data

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References

- Agency, U.S.E.P., 2017. Method 23—determination of Polychlorinated Dibenzo-P-Dioxins and Polychlorinated Dibenzofurans from Stationary Sources. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2017-0 8/documents/method_23.pdf.
- Altarawneh, M., Dlugogorski, B.Z., Kennedy, E.M., Mackie, J.C., 2009. Mechanisms for formation, chlorination, dechlorination and destruction of polychlorinated dibenzop-dioxins and dibenzofurans (PCDD/Fs). Prog. Energy Combust. Sci. 35, 245–274.
- Bo, X., Guo, J., Wan, R., Jia, Y., Yang, Z., Lu, Y., Wei, M., 2022. Characteristics, correlations and health risks of PCDD/Fs and heavy metals in surface soil near municipal solid waste incineration plants in Southwest China. Environ. Pollut. 298, 118816.
- Cao, X., Ji, L., Lin, X., Stevens, W.R., Tang, M., Shang, F., Tang, S., Lu, S., 2018a. Comprehensive diagnosis of PCDD/F emission from three hazardous waste incinerators. R. Soc. Open Sci. 5, 172056.
- Cao, X., Ji, L., Lin, X., Stevens, W.R., Tang, M., Shang, F., Tang, S., Lu, S., 2018b. Comprehensive Diagnosis of PCDD/F Emission from Three Hazardous Waste Incinerators, vol. 5. Royal Society Open Science.
- Chen, J., Mu, L., Jiang, B., Yin, H., Song, X., Li, A., 2015. TG/DSC-FTIR and Py-GC investigation on pyrolysis characteristics of petrochemical wastewater sludge. Bioresour. Technol. 192, 1–10.
- Chen, J., Zhang, J., Liu, J., He, Y., Evrendilek, F., Buyukada, M., Xie, W., Sun, S., 2020. Co-pyrolytic mechanisms, kinetics, emissions and products of biomass and sewage sludge in N-2, CO2 and mixed atmospheres. Chem. Eng. J. 397.
- Chen, T., Gu, Y.-I., Yan, J.-h., Li, X.-d., Lu, S.-y., Dai, H.-f., Cen, K.-f., 2008. Polychlorinated dibenzo-p-dioxins and dibenzofurans in flue gas emissions from municipal solid waste incinerators in China. J. Zhejiang Univ. - Sci. 9, 1296–1303.
- Chen, Z., Lin, X., Lu, S., Li, X., Qiu, Q., Wu, A., Ding, J., Yan, J., 2018. Formation pathways of PCDD/Fs during the Co-combustion of municipal solid waste and coal. Chemosphere 208, 862–870.
- Chen, Z., Lin, X., Lu, S., Li, X., Yan, J., 2019. Suppressing formation pathway of PCDD/Fs by S-N-containing compound in full-scale municipal solid waste incinerators. Chem. Eng. J. 359, 1391–1399.
- Everaert, K., Baeyens, J., 2002. The formation and emission of dioxins in large scale thermal processes. Chemosphere 46, 439–448.

- Greenwood, S., Geisenhoff, J., 2003. Incinerator slag formation and control of excursion temperatures. Water Environ. Res. 75, 314–323.
- Hajizadeh, Y., Onwudili, J.A., Williams, P.T., 2011. Removal potential of toxic 2378substituted PCDD/F from incinerator flue gases by waste-derived activated carbons. Waste Manag. 31, 1194–1201.
- He, F., Peng, Y., Wang, F., Dong, Y., Chen, K., Lu, S., 2022. Inhibition of PCDD/Fs in a full-scale hazardous waste incinerator by the quench tower coupled with inhibitors injection. Environ. Pollut. 314.
- Hinedi, Z.R., Johnston, C.T., Erickson, C., 1993. Chemisorption of benzene on Cumontmorillonite as characterized by FTIR and C-13 MAS NMR. Clay Clay Miner. 41, 87–94.
- Li, M., Wang, C., Cen, K., Ni, M., Li, X., 2017. PCDD/F emissions during startup and shutdown of a hazardous waste incinerator. Chemosphere 181, 645–654.
- Li, Q.Q., Li, L.W., Su, G.J., Huang, X.C., Zhao, Y.H., Li, B.K., Miao, X., Zheng, M.H., 2016. Synergetic inhibition of PCDD/F formation from pentachlorophenol by mixtures of urea and calcium oxide. J. Hazard Mater. 317, 394–402.
- Lin, S., Jiang, X., Zhao, Y., Yan, J., 2022. Disposal technology and new progress for dioxins and heavy metals in fly ash from municipal solid waste incineration: a critical review. Environ. Pollut. 311.
- Lin, X., Chen, Z., Lu, S., Zhang, S., Zhang, M., Li, X., Yan, J., 2018. Emission characteristics of polychlorinated dibenzo-p-dioxins and dibenzofurans from the Cocombustion of municipal solid waste in a lab-scale drop-tube furnace. Energy Fuels 32, 5396–5404.
- Lomnicki, S., Dellinger, B., 2003. A detailed mechanism of the surface-mediated formation of PCDD/F from the oxidation of 2-chlorophenol on a CuO/silica surface. J. Phys. Chem. A 107, 4387–4395.
- Lu, S., Xiang, Y., Chen, Z., Chen, T., Lin, X., Zhang, W., Li, X., Yan, J., 2021. Development of phosphorus-based inhibitors for PCDD/Fs suppression. Waste Manag. 119, 82–90.
- Ma, H.T., Du, N., Lin, X.Y., Liu, C.F., Zhang, J.Y., Miao, Z.Z., 2018. Inhibition of element sulfur and calcium oxide on the formation of PCDD/Fs during co-combustion experiment of municipal solid waste. Sci. Total Environ. 633, 1263–1271.
- Ma, Y.F., Wang, P.Y., Lin, X.Q., Chen, T., Li, X.D., 2021. Formation and inhibition of Polychlorinated-rho-dibenzodioxins and dibenzofurans from mechanical grate municipal solid waste incineration systems. J. Hazard Mater. 403.
- McKay, G., 2002. Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: review. Chem. Eng. J. 86, 343–368.
- Olie, K., Vermeulen, P.L., Hutzinger, O., 1977. Chlorodibenzo-p-dioxins and chlorodibenzofurans are trace components of fly ash and flue gas of some municipal incinerators in The Netherlands. Chemosphere 6, 455–459.
- Pan, W., Zhang, D., Han, Z., Zhan, J., Liu, C., 2013. New insight into the formation mechanism of PCDD/Fs from 2-chlorophenol precursor. Environ. Sci. Technol. 47, 8489–8498.

Sharma, A., Sharma, R.K., Kim, Y.-K., Lee, H.-J., Tripathi, K.M., 2021. Upgrading of seafood waste as a carbon source: nano-world outlook. J. Environ. Chem. Eng. 9.

Soler, A., Conesa, J.A., Ortuno, N., 2018. Inhibiting fly ash reactivity by adding N- and S-

- containing compounds. Chemosphere 211, 294–301. Stieglitz, L., 1998. Selected topics on the de novo synthesis of PCDD/PCDF on fly ash. Environ. Eng. Sci. 15, 5–18.
- Stieglitz, L., Bautz, H., Roth, W., Zwick, G., 1997. Investigation of precursor reactions in the de-novo-synthesis of PCDD/PCDF on fly ash. Chemosphere 34, 1083–1090.
- Tang, J., Xia, H., Aljerf, L., Wang, D., Ukaogo, P.O., 2022. Prediction of dioxin emission from municipal solid waste incineration based on expansion, interpolation, and selection for small samples. J. Environ. Chem. Eng. 10.
- Tuppurainen, K., Asikainen, A., Ruokojarvi, P., Ruuskanen, J., 2003. Perspectives on the formation of polychlorinated dibenzo-p-dioxins and dibenzofurans during municipal solid waste (MSW) incineration and other combustion processes. Acc. Chem. Res. 36, 652–658.
- VandenBerg, M., Birnbaum, L., Bosveld, A.T.C., Brunstrom, B., Cook, P., Feeley, M., Giesy, J.P., Hanberg, A., Hasegawa, R., Kennedy, S.W., Kubiak, T., Larsen, J.C., van Leeuwen, F.X.R., Liem, A.K.D., Nolt, C., Peterson, R.E., Poellinger, L., Safe, S., Schrenk, D., Tillitt, D., Tysklind, M., Younes, M., Waern, F., Zacharewski, T., 1998. Toxic equivalency factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. Environ. Health Perspect. 106, 775–792.
- Vehlow, J., Bergfeldt, B., Hunsinger, H., 2006. PCDD/F and related compounds in solid residues from municipal solid waste incineration - a literature review. Waste Manag. Res. 24, 404–420.
- Vermeulen, I., Van Caneghem, J., Vandecasteele, C., 2013. Indication of PCDD/F formation through precursor condensation in a full-scale hazardous waste incinerator. J. Mater. Cycles Waste Manag. 16, 167–171.
- Wang, C., Xu, J., Yang, Z., Zhang, Z., Cai, Z., 2019. A field study of polychlorinated dibenzo-p-dioxins and dibenzofurans formation mechanism in a hazardous waste incinerator: emission reduction strategies. J. Clean. Prod. 232, 1018–1027.
- Wang, P.Y., Xu, S.X., Chen, Z.L., Chen, T., Lin, X.Q., Ma, Y.F., Zhang, M.M., Li, X.D., 2020. Inhibition of polychlorinated dibenzo-p-dioxins and dibenzofurans by phosphorus-containing compounds in model fly ash. Chemosphere 257.
- Wang, Q., Jin, Y., Li, X., Chen, J., Lu, S., Chen, T., Yan, J., Zhou, M., Wang, H., 2014. PCDD/F emissions from hazardous waste incinerators in China. Aerosol Air Qual. Res. 14, 1152–1159.
- Wielgosinski, G., Namiecinska, O., Lechtanska, P., Grochowalski, A., 2016. Effect of selected additions on de novo synthesis of polychlorinated dioxins and furans. Ecol. Chem. Eng. S-Chemia I Inzynieria Ekologiczna S 23, 249–257.
- Xia, H., Tang, J., Aljerf, L., 2022. Dioxin emission prediction based on improved deep forest regression for municipal solid waste incineration process. Chemosphere 294, 133716.

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- Xia, H., Tang, J., Aljerf, L., Wang, T., Gao, B., Xu, Q., Wang, Q., Ukaogo, P., 2023. Assessment of PCDD/Fs formation and emission characteristics at a municipal solid waste incinerator for one year. Sci. Total Environ. 883, 163705, 163705.
- Xiong, S., Peng, Y., Chen, K., Lu, S., Jiang, W., Li, X., Wang, F., Cen, K., 2022. Phase distribution, migration and relationship of polychlorinated dibenzo-p-dioxins and dibenzofurans and heavy metals in a large-scale hazardous waste incinerator. J. Clean. Prod. 341.
- Xu, S.X., Chen, T., Buekens, A., Li, X.D., 2018. De novo Formation of PCDD/F during sintering: effect of temperature, granule size and oxygen content. ISIJ Int. 58, 566–572.
- Yearbook, 2022. China Statistical Yearbook. National Bureau of Statistics of China (chapter 8)-15.
- Zhan, M.X., Chen, T., Fu, J.Y., Lin, X.Q., Lu, S.Y., Li, X.B., Yan, J.H., Buekens, A., 2016. High temperature suppression of dioxins. Chemosphere 146, 182–188.
- Zhang, J., Zou, H., Liu, J., Evrendilek, F., Xie, W., He, Y., Buyukada, M., 2021. Comparative (co-)pyrolytic performances and by-products of textile dyeing sludge and cattle manure: deeper insights from Py-GC/MS, TG-FTIR, 2D-COS and PCA analyses. J. Hazard Mater. 401, 123276.
- Zhang, M., Buekens, A., Olie, K., Li, X., 2017. PCDD/F-isomers signature effect of metal chlorides and oxides. Chemosphere 184, 559–568.
- Zhang, S., Wang, F., 2022. Effect of interactions during co-combustion of organic hazardous wastes on thermal characteristics, kinetics, and pollutant emissions. J. Hazard Mater. 423, 127209.
- Zhuang, J., Tang, J., Aljerf, L., 2022. Comprehensive review on mechanism analysis and numerical simulation of municipal solid waste incineration process based on mechanical grate. Fuel 320.