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Characterization of Dioxins and Heavy Metals in Chelated Fly Ash

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Abstract: Municipal solid waste incineration (MSWI) fly ash contains highly toxic heavy metals and polychlorinated dibenzo dioxins/furans (PCDD/Fs), which are a type of hazardous waste. The pollution characteristics of fly ash have changed with the development of stoker grate incinerators and the fly ash treatment technology; however, no research has been focused on this in recent years. In this study, 12 fly ash samples were collected from 9 grate power plants in southeastern China, and their PCDD/Fs and heavy metal concentrations were determined and compared to previous fly ash data. The PCDD/Fs concentration in fly ash was in the range of 0.002–0.051 ngI-TEQ/g, with an average of 0.027 ngI-TEQ/g. Furthermore, 1,2,3,4,6,7,8-HpCDD and OCDD made the most significant contributions to PCDDs. The distribution of 10 dioxins exhibited bimodal, unimodal, and normal characteristics. Linear fitting demonstrated a strong correlation between toxicity and 1,2,3,7,8-PentaCDD, 1,2,3,7,8-PentaCDF, and 2,3,4,7,8-PentaCDF. Concerning heavy metals, Pb poses a significant environmental risk. This is the first time that fly ash treated with a chelating agent has been thoroughly analyzed, which is vital for understanding the pollution level and treatment of fly ash derived from current power plants.

Keywords: MSWI fly ash; PCDD/Fs; heavy metals

Citation: Pan, S.; Yao, Q.; Cai, W.; Peng, Y.; Luo, Y.; Wang, Z.; Jiang, C.; Li, X.; Lu, S. Characterization of Dioxins and Heavy Metals in Chelated Fly Ash. *Energies* **2022**, *15*, 4868. https://doi.org/10.3390/en15134868

Academic Editors: Robert Oleniacz and Katarzyna Grzesik

Received: 30 May 2022
Accepted: 1 July 2022
Published: 2 July 2022

1. Introduction

China's population has increased rapidly since the turn of the century, as has the level of urbanization, which has been accompanied by a rapid increase in waste production [1]. In 2020, China removed 235 million tons of waste. Landfilling is an unsustainable method of waste disposal that has expanded into the limited space along China's eastern coast [2]. China has made significant efforts to build waste incineration plants in order to address the phenomenon of "garbage siege", and its treatment capacity is increasing yearly. There are currently 463 harmless waste incineration plants in China, and waste incineration has surpassed landfills as the main from of waste disposal [3]. Municipal solid waste incineration (MSWI) effectively reduces waste, is harmless, and is internationally recognized as an advanced method of waste disposal [4]. However, MSWI fly ash has become a new pollutant. Because the dioxins and heavy metals in fly ash pose a serious threat to human health, a life cycle assessment is required to determine the long-term pollution characteristics of fly ash in the surrounding area [5].

Polychlorinated dibenzo dioxins/furans (PCDD/Fs) are highly toxic, and one of the most significant sources of these compounds is waste combustion [6]. Countries have long implemented policies that limit dioxin emissions and optimize combustion processes to

reduce dioxin generation at the source [7]. As a result of the highly polluting properties of fly ash, current related research hotspots include heat treatment, hydrothermal treatment, curing/stabilization [8], the microwave method, and photocatalysis [9–11]. In practice, treatment with fly ash chelating agents is a low-cost method. Currently, fly ash chelating agents include diacetic acid, phosphate, and dithiamine, among others, which eventually form water-insoluble, stable polymeric heavy metal ion chelates. At present, this is the primary method for treating fly ash containing heavy metals [12]. The concentration of dioxins in fly ash disposed of in landfills must meet the standard of 3 ng/g, as specified in GB16889-2008; however, for grate furnaces, the content of dioxins in fly ash is not high, and this threshold is easy to meet with the development of municipal solid waste flue gas treatment technology.

The distribution of dioxin content in fly ash is determined by waste composition, waste incineration technology, and fly ash treatment technology, among other factors. The different compositions of dioxins are very important in terms of understanding the synthetic process and the toxicity level of dioxins. Dioxins are formed in three ways: high-temperature synthesis, ab initio synthesis, and precursor synthesis [13]. Fly ash is the primary reaction surface for the formation of dioxins. The temperature distribution of flue gas in MSWI is the main reason for the formation of dioxin. The rapid cooling of flue gas below 260 °C can reduce the production of dioxins. Using a separator to separate fly ash and flue gas within a high-temperature area is also an effective means to reduce the formation of dioxins [7]. The distribution of dioxins in fly ash can be used to infer the dioxin formation process [14], which aids in the development of relevant emission standards [15].

For many years, scholars have been investigating the characteristic distribution of dioxins in China's MSWI fly ash [16,17]; however, the scope is broad, a long time has passed, and the overall pollution level of fly ash in a specific area cannot be accurately represented. In this study, 14 sets of emission data from 9 grate MSWI power plants in southeastern China were analyzed and compared with previous fly ash data from southeastern China. An air pollution control device for selective non-catalytic reduction (SNCR) denitrification + semi-dry deacidification + activated carbon adsorption + cloth-bag dedusting was adopted, and the fly ash was chelated with the polymer dithioamine. Using these data, the distribution of dioxins in grate furnaces in China was investigated. Moreover, the distribution of homologues, their main contribution and correlation to dioxin toxicity, and the heavy metal data of various fly ash samples were assessed.

2. Materials and Methods

2.1. Basic Situation of Sampling Power Plants

The fly ash was collected from 12 groups of grate furnace data from 9 MSWI power plants in a specific area of southeast China. Moreover, previous grate furnace research data from southeast China were collected [16]. The fly ash samples were labeled (GFA1, GFA2, and GFA12 denote data from this study, and the serial numbers PFA1, PFA2, and PFA6 denote data from previous research), and plant numbers are indicated by Arabic numerals (1, 2, and 15). The capacity (the tonnage of waste disposed of per day) is shown in Table 1. In this study, 12 groups of fly ash were collected from various factory ash hoppers, treated with chelating agents (dithioamine polymer and agents primarily chelating heavy metals), and tested for dioxin. Following testing, qualified fly ash was sent to a landfill for landfill treatment.

Table 1. Power plants and sampling.

Sample Number	Power Plant	Capacity	Sample Number	Power Plant	Capacity
GFA1	1	3 × 350 ton/d	GFA10	7	3 × 225 ton/d
GFA2			GFA11	8	2 × 225 ton/d
GFA3	2	2 × 500 ton/d	GFA12	9	3 × 350 ton/d
GFA4			PFA1 *	10	1000 ton/d
GFA5	3	2 × 600 ton/d	PFA2	11	2 × 600 ton/d
GFA6			PFA3	12	3 × 350 ton/d
GFA7	4	400 ton/d	PFA4	13	1500 ton/d
GFA8	5	4 × 750 ton/d	PFA5	14	1000 ton/d
GFA9	6	2 × 400 ton/d	PFA6	15	600 ton/d

* data from previous literature [16].

2.2. Sample Extraction and Analysis

The dioxin determination method for the samples was HJ 77.3-2008 isotope dilution high-resolution gas chromatography–high resolution mass spectrometry. The fly ash samples were treated with hydrochloric acid, and then washed and dried with filtered water before being extracted by dichloromethane oscillation and combined with toluene to form the extracts. The extracts were purified using a multi-layer silica gel column and separated using an activated carbon silica column for instrument analysis. The instrument model was Water AutoSpec Premier(Waters, Manchester, UK), which uses an electron-impact (EI) ion source and selective ion monitoring (SIM). The temperature program for chromatographic separation was as follows: from 130 °C (1 min) to 210 °C at 15 °C/min, then at 3 °C/min to 310 °C; then, the temperature was maintained for 8 min at 310 °C. For more details, please refer to previous research [18] and China Eco-environmental Standards HJ 77.3-2008 (Solid Waste Determination of PCDDs and PCDFs Isotope Dilution HRGC–HRMS).

Heavy metal analysis was performed using the Chinese national standard HJ/T300-2007 acetic acid buffer solution method. Inductively coupled plasma emission spectrometry HJ781-2016 (Optima 8300, PE, Singapore City, Singapore) were used for Cd, Ba, Cr, Ni, Pb, Cu, Be, and Zn analysis. Microwave digestion/atomic fluorescence HJ702-2014 (AFS-9103, Titan Instruments, Beijing, China) were used for Se and As analysis. Cold atomic absorption spectrophotometry GB/T15555.1-1995 (RA-915M, LUMEX, Vancouver, BC, Canada) were utilized for Hg, and Cr^{6+} was determined using the biphenylcarbonyl dihydrazine spectrophotometric GB/T15555.4-1995 method (TU-1810, Purkinje General, Beijing, China).

3. Results

3.1. Dioxin Emission Concentration and TEQ Level in Fly Ash

Table 2 shows the concentrations of 17 toxic dioxins and I-TEQ, 10 dioxin and furan homologues, the ratio of PCDD to PCDF, and the total amount of dioxins in the 18 samples. As can be seen in the table, the I-TEQ levels of the 12 grate fly ash samples in this study were in the range of 0.002–0.051 ngI-TEQ/g and 0.027 ngI-TEQ/g on average. The equivalent toxicity in Taiwan was reported to be 0.78–2.86 ngI-TEQ/g [19]. Moreover, the equivalent toxicity previously reported in China was 0.034–2.5 ngI-TEQ/g. Six types of grate fly ash from southeast China exhibited an I-TEQ concentration range from 0.115 to 0.645 ngI-TEQ/g [16]. The ranges in this study are much lower than those previously reported, which is largely due to the rapid development of grate furnaces and dioxin control technology in China. According to the Chinese landfill standard, all the samples met the limit of 3 ng/g, as specified in GB16889-2008.

Table 2. Data for PCDD/Fs for 18 samples (in ng/g).

PCDD/Fs	GFA1	GFA2	GFA3	GFA4	GFA5	GFA6	GFA7	GFA8	GFA9	GFA10	GFA11	GFA12	PFA1	PFA2	PFA3	PFA4	PFA5	PFA6
2,3,7,8-TetraCDD	0.004	0.008	0.004	0.003	0.001	0.001	0.002	0.003	0.001	0.000	0.003	0.001	0.039	0.0087	0.037	0.044	0.046	0.04
1,2,3,7,8-PentaCDD	0.010	0.018	0.014	0.010	0.003	0.005	0.005	0.005	0.002	0.000	0.010	0.004	0.11	0.02	0.14	0.15	0.11	0.11
1,2,3,4,7,8-HexaCDD	0.011	0.022	0.017	0.014	0.004	0.006	0.006	0.003	0.003	0.001	0.011	0.005	0.086	0.021	0.13	0.14	0.066	0.067
1,2,3,6,7,8-HexaCDD	0.026	0.057	0.028	0.021	0.008	0.013	0.019	0.020	0.009	0.002	0.024	0.013	0.64	0.075	0.27	0.42	0.13	0.13
1,2,3,7,8,9-HexaCDD	0.017	0.038	0.022	0.018	0.005	0.008	0.012	0.010	0.006	0.001	0.014	0.008	0.36	0.044	0.18	0.24	0.1	0.1
1,2,3,4,6,7,8-HeptaCDD	0.193	0.459	0.172	0.130	0.056	0.072	0.219	0.084	0.100	0.012	0.142	0.115	5	0.7	1.9	2.9	1.1	0.91
OCDD	0.291	0.843	0.248	0.167	0.103	0.094	0.632	0.267	0.403	0.041	0.252	0.408	7.2	1.4	4.8	5.2	2.4	1.7
2,3,7,8-TetraCDF	0.027	0.043	0.021	0.015	0.006	0.009	0.004	0.023	0.002	0.001	0.018	0.006	0.28	0.062	0.17	0.3	0.3	0.17
1,2,3,7,8-PentaCDF	0.027	0.061	0.027	0.019	0.011	0.018	0.008	0.019	0.005	0.001	0.031	0.009	0.42	0.099	0.44	0.55	0.48	0.41
2,3,4,7,8-PentaCDF	0.017	0.076	0.033	0.023	0.010	0.015	0.007	0.019	0.010	0.001	0.022	0.007	0.3	0.072	0.37	0.43	0.32	0.27
1,2,3,4,7,8-HexaCDF	0.029	0.067	0.031	0.020	0.020	0.031	0.019	0.011	0.012	0.002	0.036	0.016	0.35	0.076	0.47	0.42	0.35	0.42
1,2,3,6,7,8-HexaCDF	0.031	0.083	0.035	0.023	0.022	0.034	0.024	0.015	0.011	0.002	0.042	0.018	0.35	0.075	0.44	0.43	0.33	0.42
2,3,4,6,7,8-HexaCDF	0.041	0.115	0.028	0.021	0.032	0.048	0.048	0.017	0.018	0.003	0.046	0.023	0.25	0.079	0.39	0.37	0.21	0.31
1,2,3,7,8,9-HexaCDF	0.006	0.057	0.012	0.008	0.005	0.007	0.007	0.002	0.006	0.000	0.007	0.004	0.055	0.0096	0.04	0.051	0.038	0.04
1,2,3,4,6,7,8-HeptaCDF	0.077	0.234	0.092	0.057	0.073	0.095	0.120	0.016	0.059	0.006	0.097	0.057	0.61	0.23	1.3	1	0.6	1.1
1,2,3,4,7,8,9-HeptaCDF	0.011	0.052	0.017	0.010	0.013	0.017	0.034	0.003	0.008	0.001	0.016	0.013	0.15	0.05	0.17	0.16	0.1	0.24
OCDF	0.027	0.120	0.043	0.025	0.037	0.035	0.194	0.005	0.033	0.003	0.032	0.039	0.26	0.19	0.48	0.35	0.2	1.1
Total-tetradioxins	0.090	0.384	0.735	0.725	0.037	0.030	0.031	0.180	0.033	0.006	0.341	0.056	2.4	0.33	1.7	3.2	0.9	0.66
Total-pentadioxins	0.180	0.673	0.716	0.580	0.069	0.079	0.072	0.265	0.053	0.011	0.282	0.108	5.2	0.66	2.9	4.7	1.5	1.2
Total-hexadioxins	0.605	1.236	0.729	0.627	0.123	0.182	0.263	0.410	0.133	0.023	0.484	0.211	14	1.7	6	6.9	3	1.8
Total-heptadioxins	0.397	0.936	0.338	0.252	0.125	0.162	0.442	0.191	0.216	0.024	0.346	0.236	11	1.4	4.3	6	2.2	1.9
Total-OCDD	0.291	0.843	0.248	0.167	0.103	0.094	0.632	0.267	0.403	0.041	0.252	0.408	7.2	1.4	4.8	5.2	2.4	1.7
Total-PCDDs	1.563	4.073	2.767	2.351	0.458	0.548	1.441	1.312	0.838	0.104	1.704	1.019	39	5.6	20	26	10	7.3
Total-tetrafurans	0.188	0.695	0.413	0.264	0.111	0.111	0.058	0.413	0.051	0.009	0.374	0.090	7.1	1.7	6.2	11	7.3	5.2
Total-pentafurans	0.185	0.933	0.446	0.294	0.227	0.285	0.147	0.310	0.103	0.018	0.489	0.171	4.8	1.2	5.6	7	5.3	4.8
Total-hexafurans	0.171	0.473	0.160	0.110	0.220	0.334	0.231	0.080	0.071	0.018	0.234	0.146	2.9	0.71	4.1	3.8	2.8	3.6
Total-heptafurans	0.118	0.391	0.141	0.089	0.119	0.156	0.222	0.029	0.085	0.010	0.152	0.097	1.2	0.42	2	1.6	1	2.1
Total-OCDF	0.027	0.120	0.043	0.025	0.037	0.035	0.194	0.005	0.033	0.003	0.032	0.038	0.26	0.19	0.48	0.35	0.2	1.1
Total-PCDFs	0.688	2.612	1.204	0.782	0.714	0.921	0.854	0.837	0.342	0.058	1.281	0.542	16	4.2	18	24	17	17
Total(PCDDs+PCDFs)	2.251	6.685	3.970	3.134	1.172	1.469	2.295	2.149	1.180	0.162	2.985	1.561	55	9.8	38	50	27	24
PCDDs/PCDFs ratio	2.272	1.559	2.299	3.005	0.641	0.594	1.688	1.567	2.450	1.782	1.331	1.880	2.438	1.333	1.111	1.083	0.589	0.4294
I-TEQ	0.041	0.011	0.051	0.036	0.020	0.029	0.026	0.027	0.016	0.002	0.043	0.018	0.567	0.115	0.562	0.645	0.458	0.442

3.2. Toxic Dioxin Distribution in the Samples

The concentration and percentage concentration distribution of 17 toxic dioxins in 18 sample groups are shown in Figure 1. The difference in concentration in this study as compared to a previous study in vast. It can be seen in Figure 1a,c that the distribution of toxic dioxins in the grate furnace samples in this study was at a low level, especially much lower than the value shown in Figure 1e. In Figure 1b–f, it can also be seen that the main contributors to PCDD/Fs were consistent, but their relative content was different. Furthermore, 1,2,3,4,6,7,8-HpCDD and OCDD contributed the most to PCDDs, with values of 13.7–22.9% and 18.5–58.6%.

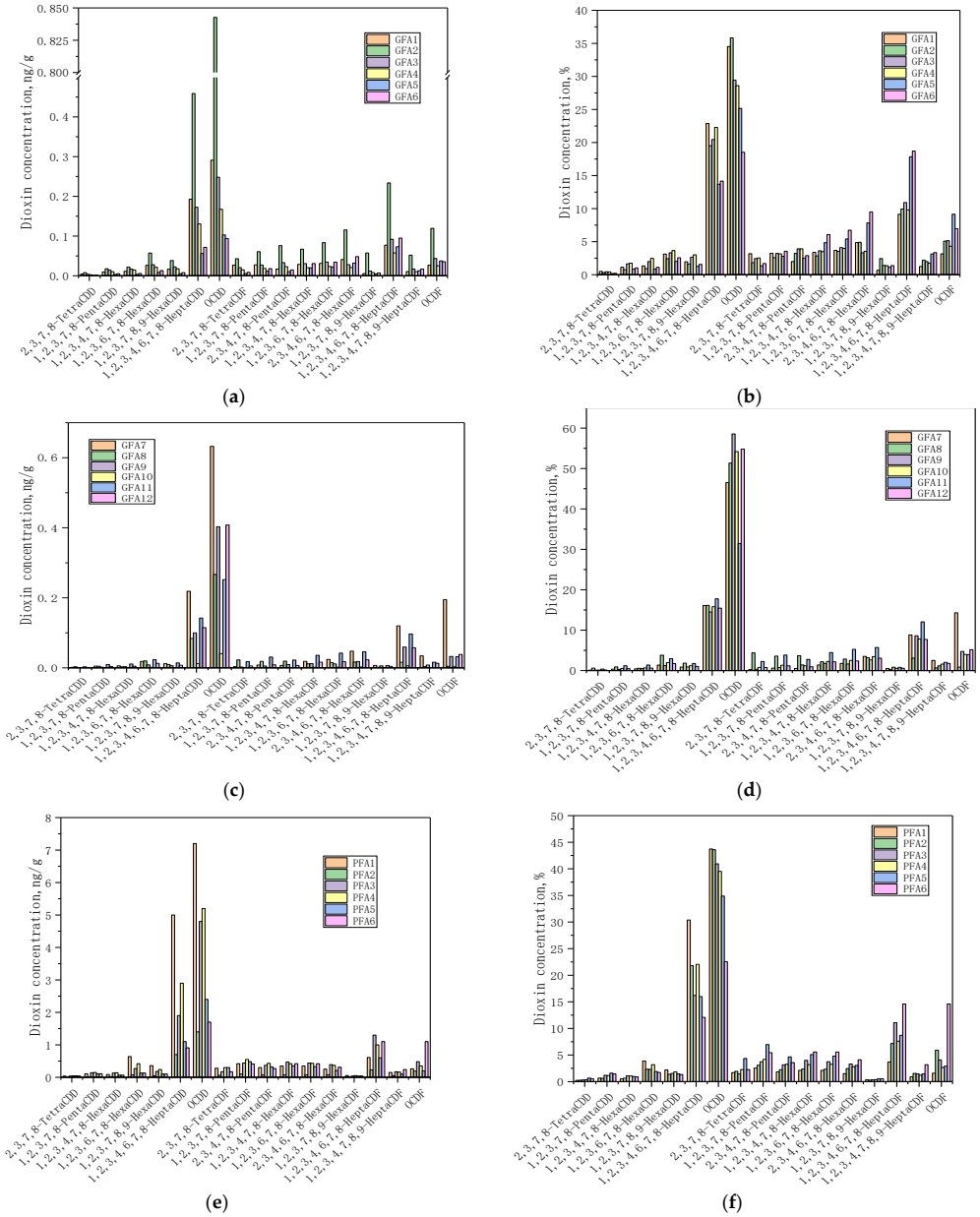

Figure 1. (**a**) Concentration distribution of PCDD/F in GFA1-GFA6; (**b**) percentage concentration distribution of PCDD/F in GFA1-GFA6; (**c**) concentration distribution of PCDD/F in GFA7-GFA12; (**d**) percentage concentration distribution of PCDD/F in GFA7-GFA12; (**e**) concentration distribution of PCDD/F in PFA1-PFA6; (**f**) percentage concentration distribution of PCDD/F in PFA1-PFA 6.

In contrast, the values in the previous study were 12.1–30.4% and 22.6–43.7%. The highest levels of PCDFs in this study were for 1,2,3,4,6,7,8-HpCDF (3.1–18.7%) and OCDF

(0.9–14.3%), which exhibited a content of 3.7–14.6% and 1.6–14.6% in six types of PFA samples (from the previous study). Other components exhibited a lower content of and a small difference in PCDFs, especially 2,3,7,8-TCDF, 1,2,3,7,8-PeCDF, 2,3,4,7,8-PeCDF, 1,2,3,4,7,8-HxCDF, and 1,2,3,6,7,8-HxCDF. This was possibly due to an insufficient amount of synthetic precursors [20].

3.3. Distribution of 10 Dioxin Homologues in the Samples

As compared with the 17 types of toxic dioxins, the distribution regularity of the 10 types of homologues was more obvious. The total homologue content distribution in the 18 types of fly ash is shown in Figure 2a,c,e. The dioxin concentration in grate furnace fly ash in this study was in the range of 0.162–6.685 ng/g, with a mean value of 2.418 ng/g, and the dioxin concentration in PFA was in the range of 9.8–55 ng/g, with a mean value of 33.97 ng/g. As can be seen, the concentration of the two is very different. It can be observed in Figure 2b that the distribution of dioxin content in GFA1-6 was more balanced and slightly bimodal, while some samples exhibited a unimodal distribution.

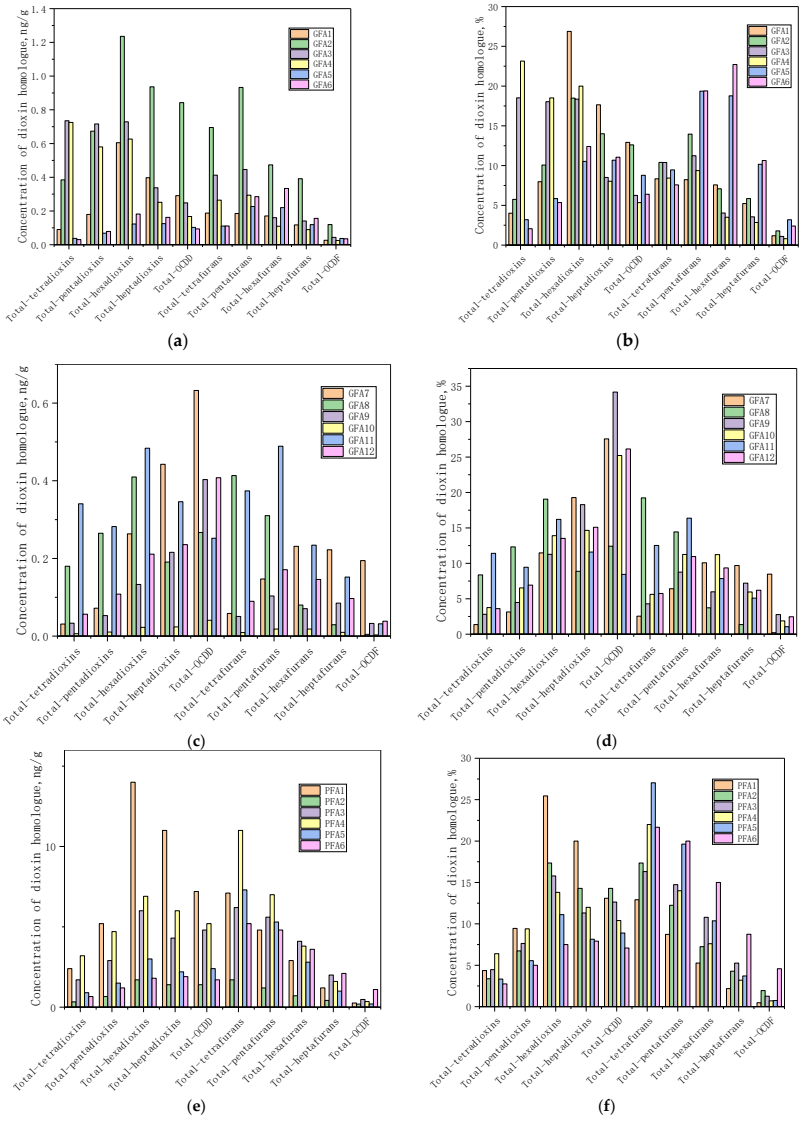

Figure 2. (**a**) Concentration distribution of 10 dioxin homologues in GFA1-GFA6; (**b**) percentage concentration distribution of 10 dioxin homologues in GFA1-GFA6; (**c**) concentration distribution of 10 dioxin homologues in GFA7-GFA12; (**d**) percentage concentration distribution of 10 dioxin homologues in GFA7-GFA12; (**e**) concentration distribution of 10 dioxin homologues in PFA1-PFA6; (**f**) percentage concentration distribution of 10 dioxin homologues in PFA1-PFA6.

The contents of Total-pentadioxins, Total-hexadioxins, and Total-heptadioxins in OCDD and Total-pentafurans and Total-hexafurans in OCDF were all higher than 10%. In Figure 2d, GFA6-12 exhibited a normal distribution characterized as high in the middle and low on both sides. OCDD (8.4–34.2%) was the highest and the others were marginally lower. In Figure 2f, the samples exhibited a distinct bimodal distribution, with Total-hexadioxins and Total-tetrafurans having the highest concentrations in PCDD and PCDF, with contents of 7.5–25.5% and 12.9–27%, respectively. In addition, the ratio of PCDD/PCDF in GFA ranged from 0.594 to 3.005, with an average of 1.756, and the PFA was in the range of 0.429–2.438, with a mean value of 1.164; thus, de novo synthesis dominated the trend in GFA [21,22].

3.4. Analysis of Dioxin Toxicity and Correlation of 17 Homologues

The analysis of the correlation between dioxins and toxic homologues was used to estimate the concentration of dioxins, which served as an important basis for distinguishing the distribution of dioxins. The data shown in Table 3 were obtained by using Excel to calculate the linear fit between 17 homologues and dioxin toxicity. In this study, the correlation coefficients of 1,2,3,7,8-PentaCDD, 1,2,3,7,8-PentaCDF, and 2,3,4,7,8-PentaCDF were very high, i.e., 0.9819, 0.9741, and 0.9735, respectively, as shown in Figure 3. They were used as indicator homologues, and the toxicity of dioxins was estimated by measuring these types of dioxins solely. This method was used in previous studies [16,23].

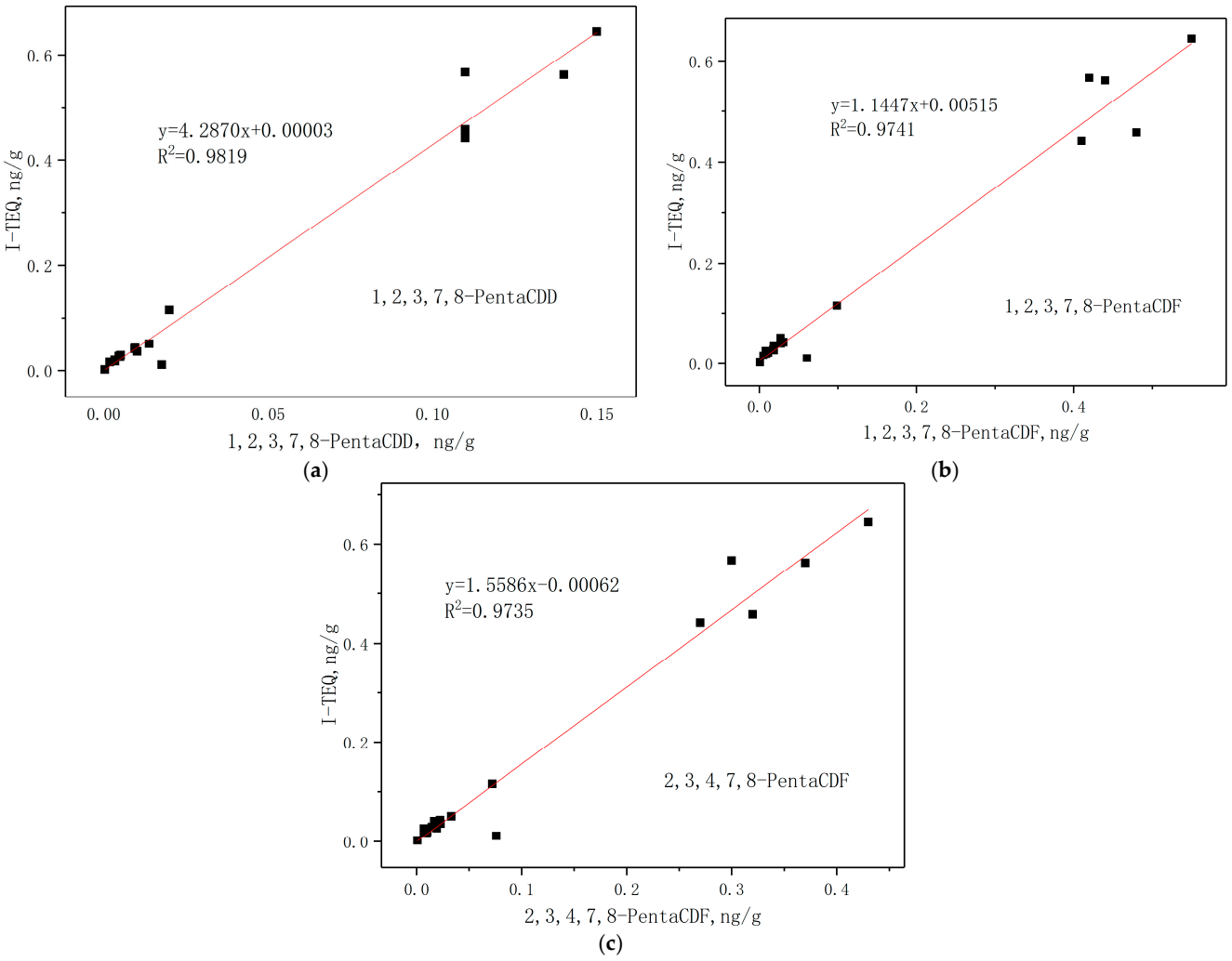

Figure 3. (**a**) Linear fit function for 1,2,3,7,8-PentaCDD; (**b**) linear fitting function for 1,2,3,7,8-PentaCDF; (**c**) linear fitting function for 2,3,4,7,8-PentaCDF.

Table 3. Relationship between dioxin homologues and dioxin toxicity.

PCDD/Fs Congeners	18 Sets of Data	
	Regression Equation	R^2
2,3,7,8-TetraCDD	12.851x − 0.00187	0.9472
1,2,3,7,8-PentaCDD	4.2870x + 0.000031	0.9819
1,2,3,4,7,8-HexaCDD	5.0952x − 0.00050	0.9263
1,2,3,6,7,8-HexaCDD	1.1691x + 0.04904	0.7288
1,2,3,7,8,9-HexaCDD	2.1281x + 0.03297	0.8007
1,2,3,4,6,7,8-HeptaCDD	0.1510x + 0.05254	0.6969
OCDD	0.1016x + 0.02329	0.8252
2,3,7,8-TetraCDF	2.0379x + 0.00806	0.9086
1,2,3,7,8-PentaCDF	1.1447x + 0.00515	0.9741
2,3,4,7,8-PentaCDF	1.5586x − 0.00062	0.9735
1,2,3,4,7,8-HexaCDF	1.3175x − 0.0014	0.9554
1,2,3,6,7,8-HexaCDF	1.3584x − 0.00732	0.9571
2,3,4,6,7,8-HexaCDF	1.7225x − 0.02329	0.9104
1,2,3,7,8,9-HexaCDF	8.9856x − 0.00372	0.6124
1,2,3,4,6,7,8-HeptaCDF	0.5239x + 0.00321	0.8475
1,2,3,4,7,8,9-HeptaCDF	2.9356x − 0.00110	0.8147
OCDF	0.5866x + 0.06933	0.4402

3.5. Distribution of Heavy Metals in Fly Ash Leaching Fluid

Heavy metals in fly ash are usually the focus of pollutants, and the content of heavy metals in different types of fly ash varies greatly [24]. Table 4 shows the results regarding the detection of heavy metals in various fly ash samples. Among the heavy metal indices, for Be, Cr, Ni, Cu, Pb, Zn, Se, Ba, Cr^{6+}, and As, the leaching concentration of fly ash was lower than the national standard. In GFA7, Hg exceeded the standard by twofold, and Cd exceeded the national standard by an order of magnitude. In GFA3, GFA10, and GFA11, Pb levels were very close to the standard value, which shows that the fly ash chelating agent is not very effective at stabilizing Pb in the fly ash tested. The concentration of Pb with low boiling point is higher in fly ash [25]. Pb also poses a high environmental risk [26], and the newly developed chelating agent should be studied in a targeted manner [27].

Table 4. Heavy metal leaching concentration of fly ash (mg/L).

Num	Be	Cr	Ni	Cu	Zn	Se	Cd	Ba	Pb	Cr^{6+}	Hg	As
GFA3	ND [1]	0.37	ND	ND	0.23	0.0022	ND	4.21	0.15	0.128	ND	0.0048
GFA4	ND	0.5	ND	ND	0.23	0.0031	ND	3.25	ND	0.124	ND	0.0065
GFA5	ND	1.06	0.101	0.017	0.02	0.019	ND	0.506	ND	1.05	0.0001	0.003
GFA6	ND	1.1	0.096	0.016	0.03	0.018	ND	0.508	ND	1.1	0.0001	0.004
GFA7	ND	ND	0.23	0.15	ND	ND	4.21	ND	0.0048	0.37	0.128	0.0022
GFA10	0.004	0.154	0.282	0.16	4	0.013	0.039	0.86	0.204	ND	0.0002	0.127
GFA11	ND	0.065	0.108	0.024	0.14	0.068	0.002	1.46	0.186	ND	0.0004	0.009
GFA12	ND	0.03	0.064	0.018	0.24	0.029	0.0029	0.68	0.0050	ND	0.0002	ND
GB [2]	0.02	4.5	0.5	40	100	0.1	0.15	25	0.25	1.5	0.05	0.3

[1] refers to undetected, [2] refers to the current general administration of quality supervision, inspection and quarantine 16889-2008: Standard for pollution control on the landfill site of municipal solid waste.

4. Conclusions

To the best of our knowledge, this is the first study to comprehensively analyze fly ash after chelating agent treatment. The fly ash tested was sampled from a large proportion of power plants in China. Grading the pollution associated with fly ash is important for understanding the current levels of fly ash dioxins in landfills. All power plants were shown to be well below the national standard for dioxin emissions, exhibiting a range of 0.002–0.051 ngI-TEQ/g, with an average of 0.027ngI-TEQ/g, and even below 50 ng/kg, which is the fly ash resource utilization standard. Among the 17 toxic dioxins, the

main contributors to PCDD/Fs were consistent, but their relative contents were different. Among the 10 dioxin homologues, the dioxin content distribution in GFA was relatively balanced, showing slightly bimodal, unipolar, and normal characteristics. In PFA, the samples exhibited a distinct bimodal distribution. In a linear fit, the correlation coefficients for 1,2,3,7,8-PentaCDD, 1,2,3,7,8-PentaCDF, and 2,3,4,7,8-PentaCDF were very high, being 0.9819, 0.9741, and 0.9735, respectively. In this heavy metals analysis, the fly ash was treated with a chelating agent, and the heavy metal content was shown to be lower than obtained with the national standard chelating agent, except for one type of fly ash. However, a good chelating effect was not observed for Pb. In addition, all the fly ash waste that was sampled and analyzed for this study is currently landfilled, consuming valuable space and resources. The problem of eradicating toxic substances has become the largest obstacle to the application of fly ash [28].

The fly ash in this study was taken solely from ash hoppers. In waste incineration plants, fly ash spreads to the surrounding environment, harming the health of on-site workers and surrounding residents. The diffused fly ash may exhibit different distributions of dioxins and heavy metals. In addition, different plants may have different tolerances to pollutants in fly ash, which may depend on the absorption of fly ash in the air and soil. This will be the focus of our next stage of research.

Author Contributions: Conceptualization, S.P. and S.L.; methodology, S.P.; software, Q.Y.; validation, Q.Y.; formal analysis, Y.P.; investigation, Y.L. and Z.W.; resources, X.L.; data curation, Y.P.; writing—original draft preparation, Q.Y.; writing—review and editing, W.C. and C.J.; visualization, Q.Y.; supervision, S.L., X.L., Y.L. and Z.W.; project administration, W.C. and C.J.; funding acquisition, W.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research and the APC was funded by the "Pioneer" and "Leading Goose" R&D Program of Zhejiang (2022C03056).

Data Availability Statement: Not applicable.

Conflicts of 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.

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