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ORIGINAL ARTICLE

Emission Factor Estimation Using Monte Carlo Simulation: Focusing on the Development of Dioxin Emission Factors in Cremation Facilities

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Abstract

In this study, data from 23 domestic cremation facilities measured for 5 years (from 2016 to 2020) of 13 domestic cremation facilities was used to calculate the emission factors of dioxins (PCDD/DFs) of cremation facilities that use Liquified Natural Gas (LNG) as combustion fuel. We performed a statistical analysis for the first time to estimate the emission factor using limited measurement results from cremation facilities that are not easily accessible. We attempted to identify the emission concentration of dioxin as a representative persistent organic pollutants substance and developed a statistically based dioxin emission factor. The concentration of dioxins (PCDD/DFs) in the cremation facility ranged 0.001–4.440 ng I-TEQ/Sm^3 with an average concentration of 0.719 ng I-TEQ/Sm^3. The emission factor calculated using the 23 measured data showed 0.010–21.485 µg I-TEQ/Cremation. A Monte Carlo Simulation was conducted using probability density distribution and parameter estimation. Consequently, 10,000 emission factors were selected, and the Pareto distribution was predicted to be the most appropriate probability density distribution. The emission factor values through Monte Carlo simulation showed a minimum value of $1.490 \times 10–08$ µg I-TEQ/Cremation and a maximum value of 7816 µg I-TEQ/Cremation. The average value was calculated as 39.920 µg I-TEQ/Cremation. Each parameter of the Pareto distribution is shape parameter (α) 1.026, location parameter (μ) – 1.021, and scale parameter (λ) 1.021. As a result of this study, the median value of the cumulative density function was selected as a representative value for the dioxin emission factor of cremation facilities and the emission factor was 0.986 µg I-TEQ/ Cremation. The 95% confidence interval in the Pareto distribution was presented as 0.026 µg I-TEQ/Cremation to 36.216 µg I-TEQ/ Cremation.

Keywords Dioxin · Emission factor · Crematorium · National dioxin emission inventory · Stockholm convention · National implementation report · Monte Carlo simulation · Pareto distribution

Introduction

Article 5 of the Stockholm Convention on Persistent Pollutants requires an emissions list to be prepared and submitted to eradicate persistent organic pollutants (POPs) unintentionally generated within the country. The Stockholm Convention proposes 10 emission source groups and 63 detailed emission sources (source categories) to calculate the emissions reported in the national implementation report. Member States of the Stockholm Convention submit national implementation reports every 4 years disclosing information on domestic POPs emission sources and emissions. In Korea, the National Report has been submitted since 2010 and the Ministry of Environment has calculated the emission factors and emission calculations for each emission source to calculate emissions according to the list of source categories. When reporting POPs emissions by country for implementing the Stockholm Convention, cremation facilities are specified as detailed emission sources. However, the Persistent Pollutant Control Act for domestic POPs management in Korea does not stipulate cremation facilities as dioxin emission facilities.

Cremation facilities are major facilities in preparation for a super-aging society and the number of deaths in Korea will increase rapidly over the next 40 years reaching about 740,000 deaths per year by 2060 according to the long-term estimates of the National Statistical Office. A survey by the National Statistical Office in 2021 showed that 89.9%

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of people aged 19 years or older preferred cremation as a funeral method. As cremation is a common practice in many societies to destroy the human body by burning, it is a major facility in society and a continuous increase in its use is expected in the future. Therefore, discussions on expanding cremation facilities in Korea are ongoing to prepare for a super-aged society.

The main pollutants in the cremation facilities are CO, NOx, SO2, VOC which are gaseous pollutants and PM10, PM2.5 which are particulate matter [1]. In addition, organic pollutants include Polychlorinated dibenzo-p-dioxin/dibenzofurans(PCDDs/DFs), polynuclear aromatic hydrocarbons(PAHs) and other Radioactive substances used in anticancer treatment [2, 3].

This was a basic study to check the emission concentration and status for future POPs management in cremation facilities. In particular, access to crematoriums for research is hardly acceptable owing to the nature of the facility. Therefore, there has always been a limitation on the number of field measurements. In this study, we conducted a statistical analysis for the first time to estimate emission factors using limited measurement results from cremation facilities that were not easily accessible. We attempted to identify the emission concentration of dioxin as a representative POPs substance and developed a statistically based dioxin emission factor.

Methods

Selecting Research Target Facilities and Collecting Samples

As of September 2022, there were 62 cremation facilities in operation in Korea with 12 facilities in Gyeongbuk province, 10 in Gyeongnam province, 8 in Gangwon province, and 7 in Jeonnam province. This study used data from 23 domestic cremation facilities measured for 5 years (2016–2020) of 13 domestic cremation facilities to calculate the emission factors of dioxins (PCDD/DFs) of cremation facilities that use Liquified Natural Gas(LNG) as combustion fuel.

In general, it has been investigated that cremation facilities use LNG, liquefied petroleum gas(LPG), diesel, kerosene and by-product fuel as auxiliary combustion fuels [4, 5].

General information on the targeted 13 facilities in this study and the status of the air pollution control facilities are presented in Table 1 and Fig. 6. Cremation facilities are operated daily and the operating hours per day are 3–10 h, which vary by facility and crematorium unit. Field measurements for each cremation facility were performed one to three times over 5 years. Table 2 shows dioxin generation and emission factors of each 13 cremation facility measured in’16–’20.

Table 1 General information of the targeted 13 facilities in this study

target facility	Annual cremation cases[a]	Number of measurements	year
CR-A	10,329	2	‘18,’20
CR-B	14,392	2	‘18,’19
CR- C	8445	2	‘16,’18
CR-D	4253	1	‘20
CR-E	18,445	1	‘20
CR-F	32,105	3	‘16 ‘17, 20
CR-G	14,252	1	‘16
CR–H	10,792	2	‘16, ’18
CR-I	8932	1	‘17
CR-J	23,377	3	‘16, ’17, ‘20
CR-K	5352	1	‘20
CR–L	11,680	2	‘16, ’17
CR-M	3361	2	‘17, ’18
13 cremation facilities	–	23	

[a] ‘Total number of cremations per year at the facility as of 2020

Sampling and Analysis Method

To collect samples from the crematorium, a field survey was conducted in advance to identify the process flow, operating conditions, and status of the measurement points (for example, stack height, inner diameter, and location of measurement points) of the target facility.

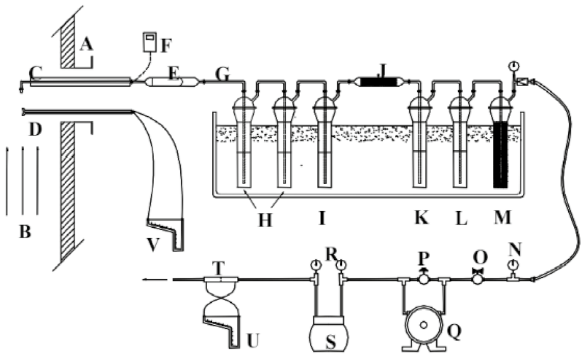
Sampling and analysis were conducted according to Korea’s Persistent Pollutant Process Test Standards (Notice No.2022-37 of the National Institute of Environmental Research). Figure 1. presents the composition of sampling equipment and Fig. 2 shows the status of dioxin measurement equipment installation during on-site measurement at a cremation facility.

Sample collection was performed at a constant speed during the cremation time (approximately 1.5–2 h) of one body and 37Cl4-2,3,7,8 TCDD 2 ng (EPA-1613CSS, Wellington Inc., Canada) was injected into the Amberlite® XAD-2 (SUPELCO™) resin to control the quality of sample collection. 37Cl4-2,3,7,8 TCDD is an internal standard for sample collection. The recovery rate of the internal standard material for sample collection is calculated during instrumental analysis in order to determine the influence of the media and errors in the overall sample collection process. And Amberlite® XAD-2 is a styrene divinylbenzene series porous polymer adsorption resin.

After measuring the amount of moisture in the exhaust gas, the flow rate, velocity, and temperature at the measuring

Table 2 Dioxin concentration and Emission factor of each cremation facility measured in ’16–’20

Cremation facility	Year	Sampling time	① Dioxin (PCDD/DFs) Concentration	② Flowrate	③ Number of cremations per an hour	①×②÷③×10^{-3} Emission Factor	PCDD/DFs Concentration (Standard Oxygen Conc.12% Corrected)	Actual Oxygen Conc
			C_{sample}	$Q_{emission\ gas}$	$N_{cremation}$		$C_{sample\ (O2\ 12\%\ Corrected)}$	Oxygen Conc
		min	ng I-TEQ/Sm^3	Sm^3/h	Cremation/h	μg I-TEQ/ Cremation	ng I-TEQ/Sm^3	%
CR-A	’18	70	0.122	5671	1	0.689	0.336	17.7
	’20	60	2.892	2527	1	7.307	6.053	16.7
CR-B	’18	80	0.307	7367	1	2.265	0.628	16.6
	’19	60	0.570	3335	1	1.901	1.021	16.0
CR-C	’16	65	0.001	9552	1	0.010	0.002	15.2
	’18	65	0.050	3553	1	0.178	0.078	15.2
CR-D	’20	60	0.052	1463	1	0.076	0.100	16.3
CR-E	’20	55	2.494	809	1	2.017	3.091	13.7
CR-F	’16	65	0.595	36,110	1	21.485	0.676	13.1
	’17	70	0.563	10,371	1	5.838	1.291	17.1
	’20	45	0.152	7168	1	1.089	0.387	17.5
CR-G	’16	65	0.004	23,023	1	0.092	0.008	16.3
CR–H	’16	70	0.214	11,110	1	2.378	0.303	14.6
	’18	95	0.022	5052	1	0.111	0.036	15.4
CR-I	’17	90	0.410	5480	1	2.244	0.796	16.4
CR-J	’16	60	0.586	30,548	1	17.901	2.110	18.5
	’17	100	1.475	13,935	1	20.558	8.112	19.4
	’20	70	4.440	3687	1	16.371	11.853	17.6
CR-K	’20	40	0.180	2582	1	0.465	0.248	14.5
CR–L	’16	60	0.689	28,050	1	19.326	1.101	15.4
	’17	60	0.393	5172	1	2.034	0.584	14.9
CR-M	’17	80	0.151	5880	1	0.888	0.769	19.2
	’18	85	0.185	12,405	1	2.297	0.660	18.5
Average		68	0.719	10,211	1	5.544	1.750	16.3
Max		100	4.440	36,110	1	21.485	11.853	19.4
Min		40	0.001	809	1	0.010	0.002	13.1



A: Stack
B: Exhaust gas flow direction
C: Suction tube
D: S type pitot tube
E: Filter holder
F: Heat conduction thermometer
G: Connecting tube
H: Impinger (Distilled water)
I: Impinger (Empty bottle)
J: Absorption tube
K: Impinger (Diethylene glycol)
L: Impinger (Empty bottle)
M: Impinger (Silica gel for dehumidification)
N: Vacuum gauge
O: Main control valve
P: Bypass
Q: Vacuum pump
R: Thermometer
S: Dry gas meter
T: Orifice
U: Orifice manometer
V: Pitot manometer

Fig. 1 Composition of sampling equipment

Fig. 2 Current Status of Cremation Facility Sampling Site Equipment Installation

point were measured every 5 min during sampling. As monitoring exhaust gas oxygen content is essential for efficiency, emission control, and regulatory compliance in air pollution emission facilities, the oxygen content was continuously measured at 1-min intervals using an automatic exhaust gas analyzer (MRU Instruments, Inc. PG-250/350).

After sampling was completed for each crematorium, the collected absorption liquid was transferred to the laboratory in a brown glass bottle. The impinger, suction tube and nozzle used for sampling were washed with toluene and acetone, called the washing liquid. The absorption liquid (Diethyl glycol solution) and washing liquid were mixed for liquid/liquid extraction.

The cylindrical filter paper and adsorbent resin (Amberlite® XAD-2) were extracted with 300 ml of toluene using a Soxhlet/Dean-Stark extractor for over 16 h. The in-laboratory extraction method for PCDD/DFs analysis for each filter, resin, absorbent, and cleaning solution used for field sampling is shown in Fig. 3.

After mixing the liquid and solid extracts and concentrating them to 10–20 mL using a rotary evaporator, a portion was aliquoted for PCDD/DFs analysis. Fifteen types of 13C-labelled PCDDs/DFs 1 ng (EPA-1613LCS, Wellington Inc., Canada) were injected as standard materials for Cleanup.

The Cleanup of the sample was carried out in the order of a multi-layer silica gel column and an alumina column to remove interfering substances such as organic matter, color-inducing substances and polychlorinated biphenyls (PCBs) present in the sample. If the Cleanup was insufficient, the product was purified using an activated carbon column. Gas chromatography coupled with mass spectrometry (GC-HRMS) was used for analysis.

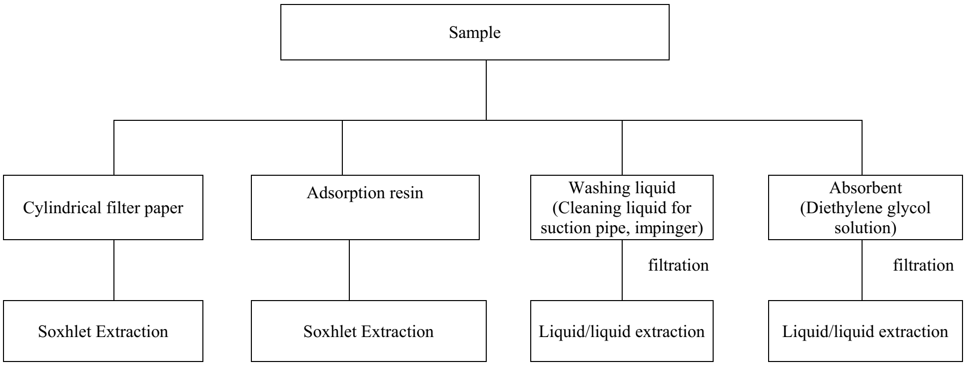
The purified sample was injected with 1 ng (EPA-1613ISS, Wellington Inc., Canada) of two types of 13C-labelled PCDDs/DFs as standard materials for syringe and finally concentrated to about 50 µl for gas chromatography and high resolution. The samples were analyzed using a mass spectrometer (JMS800D Ultra Focus, Japan).

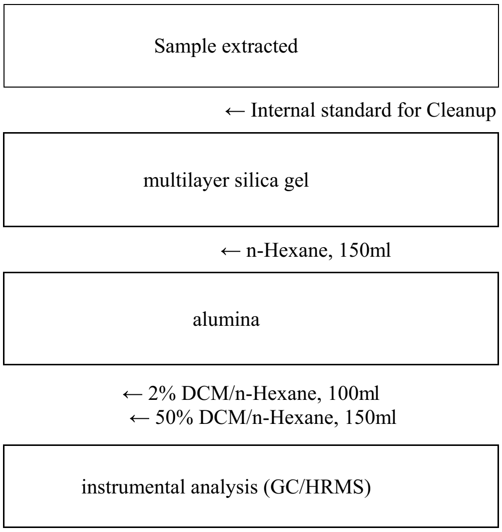
The analytical conditions of the instrument are shown in Fig. 4. The substances to be analyzed were 2,3,7,8 substituted isomers (17 isomers) with designated toxicity equivalent conversion factors and International Toxicity Equivalency Factors (I-TEFs) were applied to the actual concentration of each substance to calculate the Toxic Equivalents (TEQ) as a 2,3,7,8-TCDD concentration. SP-2331(a strongly polar column) was used to determine the elution order of each isomer in the chromatogram. When the sensitivities for seven and eight chlorides were low, they were combined with a DB-5MS UI column.

Cremation Facility Emission Factor Calculation Method

The emission factor was calculated as the dioxin emission mass per unit of cremation and the unit was expressed as micrograms (µg) per cremation. To calculate the emission factor, the emissions by the facility were calculated using the measured concentrations of PCDD/DFs and the exhaust gas emission flow rate of each facility and the emission factor by the facility was calculated by dividing each emission by the number of cremations per hour (1 cremation/h):

Fig. 3 Extraction method for PCDD/DFs analysis





Item	Condition
Type of Column	SP-2331:60m×0.32mm ID×0.2 µm DB-5MS UI:60m×0.25mm ID×0.2 µm
Carrier gas	He (99.9999%) at 1.0 ~ 1.4 mL/min
Injection Temp.	260 °C ~ 280 °C
Type of Injection	splitless
Temperature rising condition	SP2331: 120°C(1min) →200°C (3 min, 20°C/ min) → 260(25 min, 5°C/ min) DB-5MS UI: 150°C(1min) →250°C (0min, 10°C/min) →300(5min, 5°C/ min)

Fig. 4 Cleanup procedure and GC/HRMS instrumental analysis conditions for PCDD/DFs

$$EF = C_{\text{sample}} \times Q_{\text{emission gas}} \div N_{\text{cremation}} \times 10^{-3},$$

EF is the Emission Factor (µg I-TEQ/Cremation), C_{sample} is the TEQ concentration of PCDDs/DFs in the emission gas (ng I-TEQ/Sm^3), $Q_{\text{emission gas}}$ is the flow rate of emission gas (Sm^3/h), $N_{\text{cremation}}$ is the number of cremations per hour (Cremation/h), and time required for each cremation was set to 1 h (60 min).

The sampling time for the actual concentration measurements at each facility was 40–100 min and the average sampling time was 68 min. Conversely, it took an average of 60 min to burn a corpse in a crematorium facility according to a survey [4]. This study calculated the emission factor by setting the time required for each cremation to 60 min. The emission factor was calculated based on data measured at the crematorium and the optimal probability density function was confirmed using the 23 calculated emission factors.

Understanding the distribution of data can help visualize the data, and we attempted to identify the best distribution fit for our dataset. The distributions relevant to this study are the t-distribution, Pareto distribution, and Weibull distribution.

T-distribution is bell-shaped and symmetrical at $t = 0$. What determines the shape of the t-distribution is the degree of freedom, and as the degree of freedom increases, it gets closer to the standard normal distribution [6]. The Pareto distribution is characterized by its long-tailed shape, which reflects the power-law behavior. It models phenomena where a small fraction of extreme events contributes significantly to the overall distribution [7]. The Weibull distribution is a continuous probability distribution commonly used to model a broad range of random variables, largely in the nature of a time to failure or time between events [8].

A probability density function (PDF) represents the distribution of a random variable and the value obtained by integrating the function over a specific interval becomes the probability value included in the interval [6].

The cumulative distribution function (CDF) describes the probability that a random variable is less than or equal to a certain value for some probability distribution. Differentiating the CDF results in PDF, and conversely, integrating the PDF results in CDF [9].

A Monte Carlo simulation (using random sampling) was performed by applying the optimal probability density function and the probability density distribution with the highest goodness-of-fit was selected based on 10,000 Monte Carlo simulations. Finally, the emission factor representing the probability density distribution was calculated and a 95% confidence interval was confirmed. In this study, Python was used as a tool to assume the probability density function and perform Monte Carlo simulations. The procedure for calculating the emission factor is presented in Fig. 5.

Results and Discussion

Management of Dioxin Pollution in Cremation Facilities

A general cremation facility consists of primary and secondary incineration chambers. Subsequently, the operating fuel is input for continuous combustion for approximately 1–1.5 h and the combustion continues.

Research results on dioxin emissions from cremation facilities suggest that pesticide- and preservative-treated caskets, fuel (LNG, LPG, Diesel, Kerosene, By product of

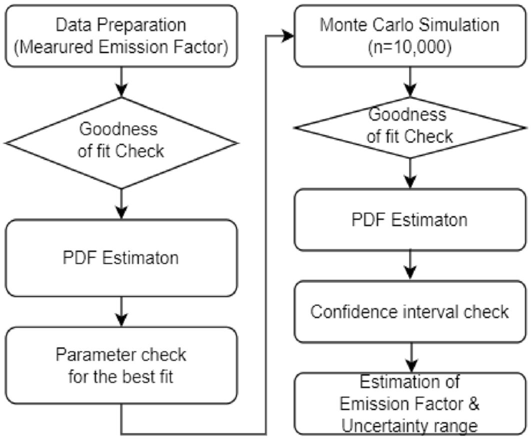


Fig. 5 Procedure for Emission Factor Calculation

fuel) and remains are the main sources of dioxins that affect their generation of major dioxins [10, 11].

Items such as PVC and metals injected into a combustion furnace can cause the incomplete combustion of chlorine compounds and de novo synthesis reactions, which can act as sources of dioxins [12].

The status of air pollution prevention facilities for cremation facilities is shown in Fig. 6 and the general composition of prevention facilities includes particulate matter removal, acid gas treatment [13].

Among the 13 cremation facilities investigated in this study, five were Cyclone + Bag filter combinations and four were Cyclone + Bag filter + catalytic reaction facility combinations.

In most facilities surveyed in this study, preventive facilities for the physical treatment of particulate matter were installed and operated with considerable emphasis.

As a dioxin control measure in most facilities, activated carbon was added and adsorbed during bag filter operation, and catalytic reactions such as SCR were applied in some facilities.

Cremation Facility Dioxin Concentration Analysis Results

As a result of a total of 23 measurements conducted at 23 cremation facilities using LNG fuel between 2016 and 2020, the concentration of dioxin (PCDD/DFs) in cremation facilities was shown in the range of 0.001 ~ 4.440 ng I-TEQ/Sm^3 and the average concentration was 0.719 ng I-TEQ/Sm^3. The concentration status of each facility is presented in Fig. 7.

However, the Persistent Pollutant Control Act for domestic POPs management in Korea does not stipulate cremation facilities as dioxin emission facilities. Therefore, dioxin emission standards for cremation facilities have not yet been established.

To confirm the level of dioxin emission concentration in cremation facilities, an emission allowance standard was established for a newly established municipal solid waste incineration facility with an incineration capacity of less than 2 tons to 25 kg or more per hour. A comparison of the concentrations from cremation facilities and municipal solid waste incineration facilities revealed that the emission concentrations of cremation facilities were lower than the emission standards for incineration facilities.

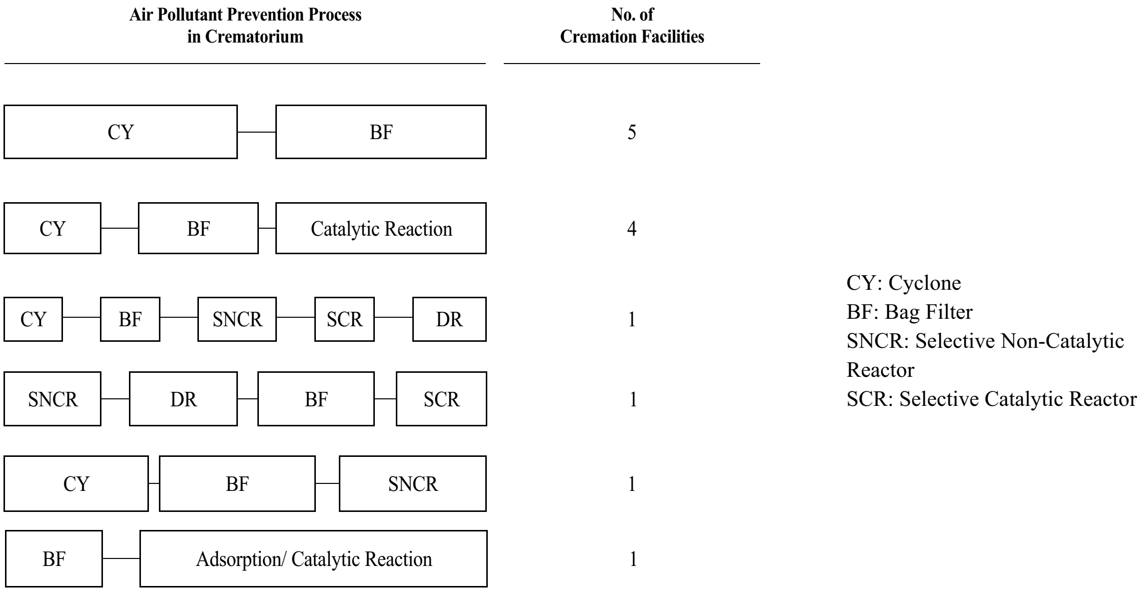


Fig. 6 Air pollution prevention facilities in crematoriums

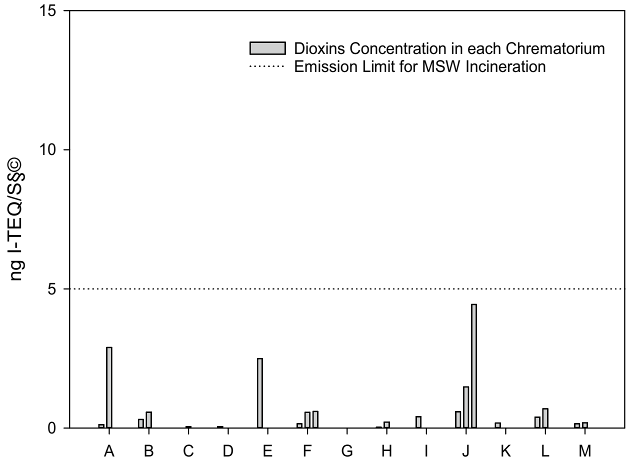


Fig. 7 Concentration status by facility (Actual measured concentration)

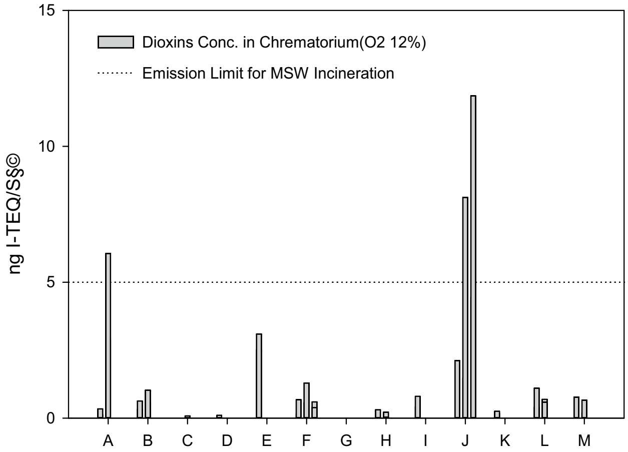


Fig. 8 Concentration status by facility (Standard oxygen conc. 12% applied)

However, caution is required when interpreting the dioxin concentration comparison results. This is because a difference in concentration may occur depending on whether a standard oxygen concentration is applied. In other words, the concentration of dioxin in the cremation facilities presented in this study was presented as an actual concentration without correcting the standard oxygen concentration. However, in the case of municipal solid waste incineration facilities a standard oxygen concentration of 12% was applied and corrected to prevent the concentration dilution effect due to the excess oxygen concentration. Therefore, when the standard oxygen concentration was corrected for the emission concentration at the cremation facility, a dioxin concentration higher than the actual measured concentration was estimated.

Suppose the actual dioxin concentration measured in the cremation facilities in this study is corrected by applying a standard oxygen concentration of 12% to municipal solid waste incineration facilities and the result of each facility is shown in Fig. 8.

In that case, the average emission concentration of the 23 samples is 1.750 ng I-TEQ/Sm^3, which is approximately 2.4 times increased than the uncorrected concentration (0.719 ng I-TEQ/Sm^3).

In addition, after applying the standard oxygen concentration correction, the concentrations of 3 out of 23 samples (approximately 13% of the surveyed samples) exceeded 5 ng I-TEQ/m^3, which is the emission standard of municipal solid waste incineration facilities.

In the case of cremation facilities, it was confirmed that they were operated under an average oxygen concentration of 16.3% during combustion as they were operated under conditions of excess air for complete combustion. It was assumed that the concentration in the cremation facility was underestimated.

Therefore, it is necessary to consider the air dilution effect when managing the concentration of dioxins in cremation facilities and to operate the facility more closely in preparation for the application of standard oxygen concentration correction when preparing emission standards in the future:

$$C_s = C_a \times \frac{21 - O_s}{21 - O_a},$$

C_s is the concentration corrected for standard oxygen concentration (ng I-TEQ/ Sm^3), C_a is the concentration uncorrected for standard oxygen concentration (ng I-TEQ/ m^3), O_a is the oxygen concentration (%), O_s is the standard oxygen concentration (%), and 12% Standard Oxygen concentration was applied which is for a newly installed municipal waste incineration facility.

Estimation of Probability Density Distribution

The emission factor calculated using the 23 measured data showed a value of 0.010–21.485 µg I-TEQ/Cremation (Fig. 9).

The probability density function was confirmed using 23 emission factors calculated from the field-measured concentration and flow data (Fig. 10). As a result of checking, the three distributions with the lowest Residual sum of squares (RSS) were the *t* distribution, the Pareto distribution, and the Weibull distribution and the RSS of the distributions were 0.002, 0.005, and 0.007, respectively (Table 3):

$$\mathrm{RSS} = \sum_{i=1}^{n} \left(y_i - f(x_i)\right)^2,$$

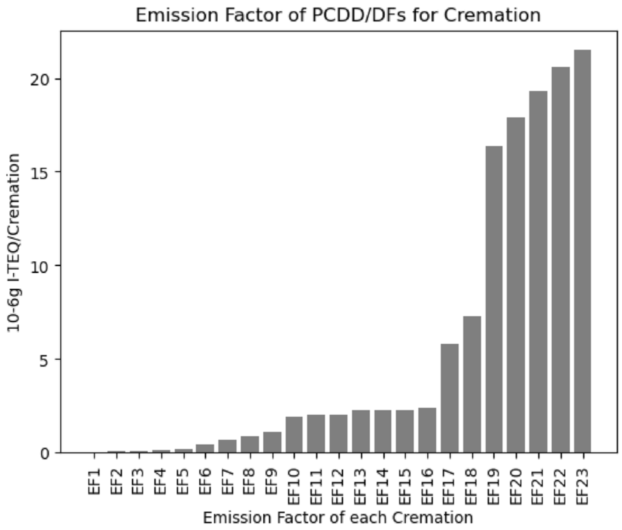


Fig. 9 Measured EF for Cremation ($n=23$)

y_i is the ith value of the variable to predict, x_i is the ith value of the explanatory variable, and $f(x_i)$ is the predicted value of y_i.

As a result of confirming the distribution with the lowest RSS value as the distribution that best predicted the distribution of the measured data, the t-distribution was calculated as the best predictor of the distribution of the measured data. However, as the t-distribution includes a range of negative numbers in the estimation range of the emission factor it was excluded when selecting the optimal distribution in this study in which the actual number must be predicted. Therefore, 23 measured data were predicted to follow the Pareto distribution and the parameters of the predicted Pareto distribution were calculated as Shape (α) 1.003, location (μ) – 1.716 and Scale (λ) 1.726.

The Pareto distribution is based on the Pareto principle ("80–20 rule"), which states that 80% of the effects are due to 20% of the causes.

According to empirical observations, this 80–20 distribution is suitable for various cases including natural phenomena [14] and human activities, such as environmental pollution [15, 16].

In other words, the value corresponding to a 20% interval of the emission factor value accounted for 80% of the total number of emission factors.

The Pareto distribution has a Pareto tail, meaning that the probability of an event decreases as it increases. The Pareto cutoff is the point at which this tail ends and the probability of an event becomes negligible [14].

The Pareto distribution is specified using shape parameter (α), location parameter (μ) and scale parameter (λ). The shape parameter (α) changes the shape of the distribution.

Fig. 10 PDF Plot of measured EF ($n=23$)

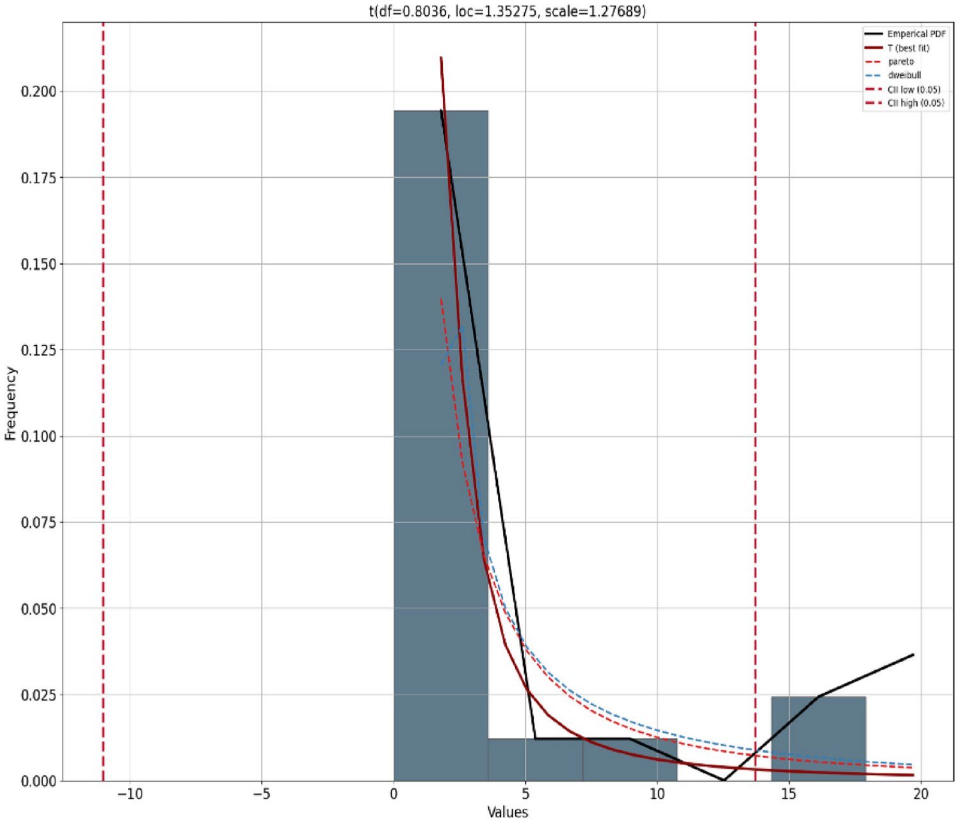


Table 3 Goodness of fit and parameters for PDF (Based on the actual measured data ($n = 23$))

Distribution	RSS	Loc	Scale	Shape
t	0.002	1.353	1.277	–
Pareto	0.005	– 1.716	1.726	1.003
Weibull	0.007	2.244	5.284	–

The location parameter (μ) moves the entire distribution to the left or right and the scale (λ) parameter compresses or expands the entire distribution.

Depending on the assumption conditions for each type of Pareto distribution, they are classified into Types I–IV. The probability density function and assumption conditions for each type are as presented in Table 4 [17]:

Among the Pareto distributions, the Type I probability density function is expressed as follows:

$$f(x) = \begin{cases} \frac{\alpha\lambda^\alpha}{x^{\alpha+1}} & x \geq \lambda \\ 0 & x < \lambda \end{cases},$$

where α is the shape parameter, λ is the scale parameter

In this study, the emission factor must be predicted as a real value and the minimum x value is greater than μ. Therefore, the probability density distribution for the 23 measurement results was confirmed to follow Type II among the Pareto distribution types. The probability and cumulative density functions are expressed in equations (Eqs. 1, 2). In addition, the parameters for Pareto distribution Type II and formulas for calculating the average, median, mode and variance are also presented in Table 5 [17, 18].

Pareto (Type II) probability density function

$$f(x) = \frac{\alpha\lambda^\alpha}{(x+\lambda)^{\alpha+1}} \tag{1}$$

where α : shape parameter, λ : scale parameter

Pareto (Type II) cumulative density function

$$F(x) = \left[1 + \frac{x-\mu}{\lambda}\right]^{-\alpha},\ x \geq \mu \tag{2}$$

Table 4 Types of Pareto distribution

Type of pareto Distribution	Support	Parameter
Type I	$x \geq \lambda$	$\lambda > 0, \alpha$
Type II	$x \geq \mu$	$\mu \in R, \lambda > 0, \alpha$
Lomax	$x \geq 0$	$\lambda > 0, \alpha$
Type III	$x \geq \mu$	$\mu \in R, \alpha, \gamma > 0$
Type IV	$x \geq \mu$	$\mu \in R, \lambda, \gamma > 0, \alpha$

Table 5 Parameter and moment of Pareto typeII

Parameter	Shape (α) > 0 Scale (λ) > 0
Support	$x \geq \mu$
Mean	$\frac{\lambda}{\alpha-1}$
Median	$\lambda(\sqrt[\alpha]{2} - 1)$
Mode	0
Variance	$\frac{\lambda^2\alpha}{(\alpha-1)^2(\alpha-2)}$ $\alpha > 2$ ∞ $1 < \alpha < 2$ Undefined otherwise

where α is the shape parameter, μ is the location parameter, and λ is the scale parameter.

Conduct Monte Carlo Simulation

Ten thousand simulations were conducted using the shape parameter value (α) of 1.003 of the Pareto Distribution, which is the optimal probability density distribution derived based on the 23 field measurement results (Fig. 11). The probability density distribution was then confirmed using 10,000 emission factor values derived from the simulation results. The 10,000 emission factor values randomly selected through Monte Carlo simulation were calculated as a minimum value of 1.490×10^{-08} μg I-TEQ/Cremation, a maximum value of 7,816 μg I-TEQ/Cremation and an average value of 39.920 μg I-TEQ/Cremation (Figs. 12, 13).

The RSS value was checked to confirm the goodness of fit of the probability density distribution for 10,000 emission coefficient values and the RSS values corresponding to each probability density distribution are presented in Fig. 11. As a result of calculating the RSS value of each probability density function, the distribution with the lowest RSS value was confirmed to be the Pareto distribution. For each parameter of the Pareto distribution, the shape parameter (α) is 1.026, the location parameter (μ) is -1.021 and the scale parameter (λ) is 1.021.

The 95% confidence interval for the Pareto-distributed emission factor population was calculated from 0.026 μg I-TEQ/Cremation to 36.216 μg I-TEQ/Cremation. In addition, the median value of the cumulative density function (CDF) was 0.986 μg I-TEQ/Cremation. Meanwhile, emission factors smaller than 10 μg I-TEQ/Cremation accounted for 90.6% of the total emission factors (Fig. 14).

Among 10,000 emission factors randomly selected through Monte Carlo simulation, a cumulative probability density of 80% corresponding to the Pareto Cutoff was calculated as 5.824 μg I-TEQ/Cremation, which means that the emission factor value below 5.824 μg I-TEQ/Cremation is the majority of all the emission factors.

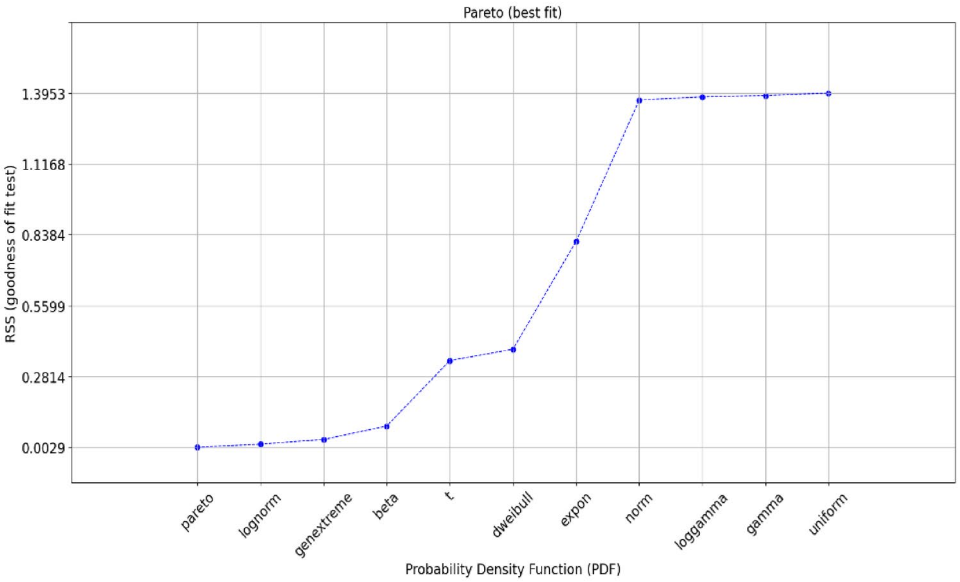


Fig. 11 Goodness of fit test (RSS) result (Based on Monte Carlo Simulation (n = 10,000))

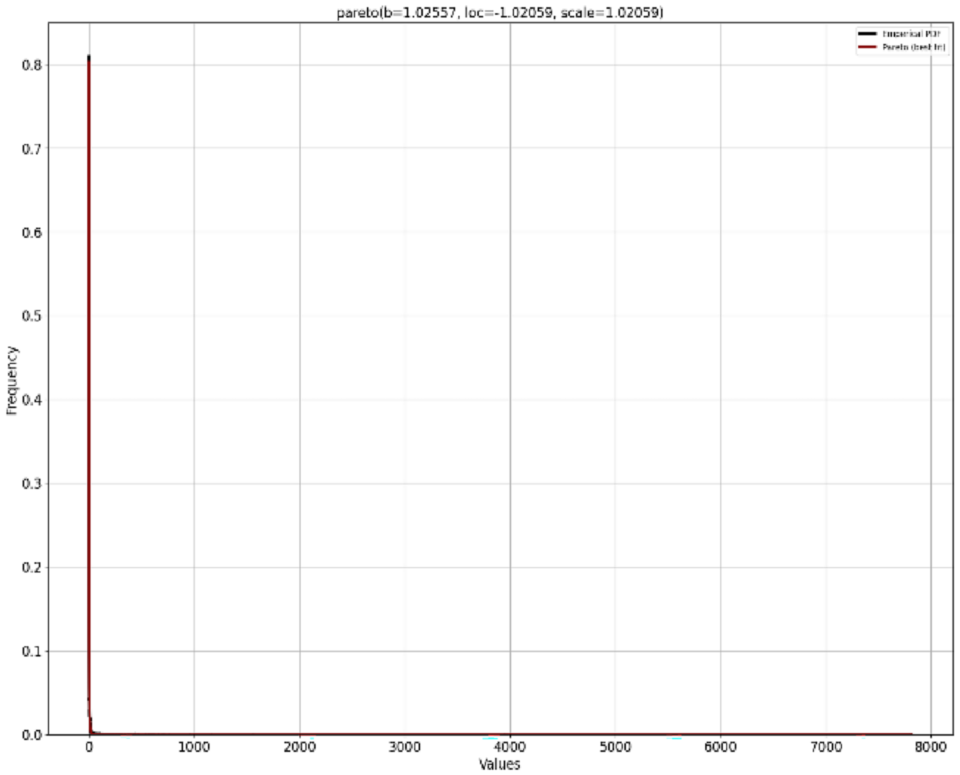


Fig. 12 PDF Plot of Monte Carlo Simulation (Full Range)

In this study, we attempted to calculate the emission factor using Monte Carlo simulations to determine the dioxin emission factor of the crematorium. The field measurements and simulation results confirmed that the dioxin emission factor values of the crematory facility were distributed over a wide range and exhibited a Pareto distribution, in which the emission factor values were concentrated in some sections.

In the results of this study, the median value of the cumulative density function was selected as a representative value for the dioxin emission coefficient of cremation facilities and the emission factor value was calculated as 0.986 µg I-TEQ/Cremation.

The 95% confidence interval was calculated from 0.026 µg I-TEQ/Cremation to 36.216 µg I-TEQ/Cremation.

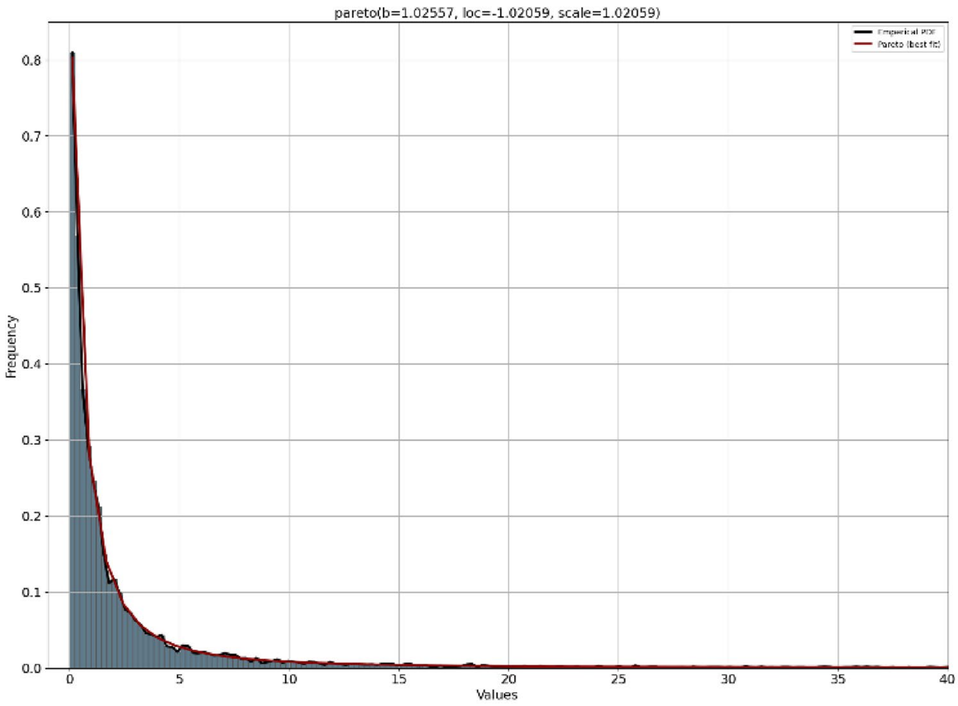


Fig. 13 PDF Plot of Monte Carlo Simulation (Range 0–50 μg I-TEQ/Cremation)

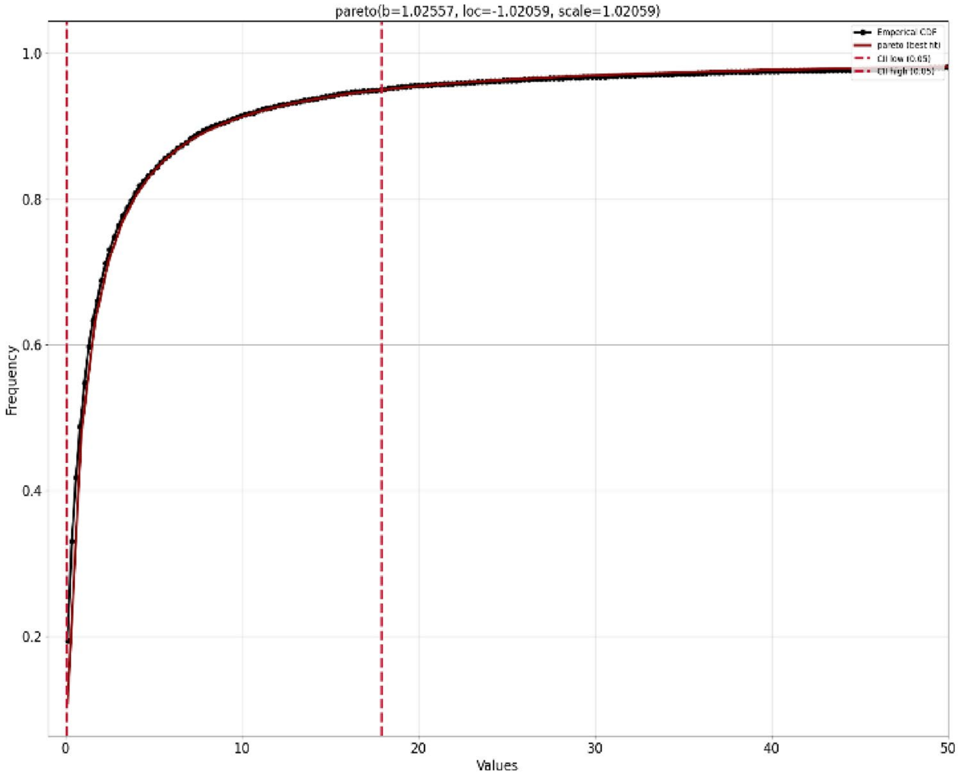


Fig. 14 CDF Plot of Monte Carlo Simulation (Range 0–50 μg I-TEQ/Cremation)

In conclusion, the dioxin emission factor of domestic cremation facilities was calculated to be 0.986 μg I-TEQ/Cremation and the confidence interval was – 97% to 3573%.

Comparison of Previous Research Results

A review of the results of previous studies related to the calculation of the dioxin emission factors of cremation facilities is presented in Table 6. We reviewed the results of

Table 6 Study result about dioxin emission factor in Cremation

Study result	This study		Yu (1998) [5]		Wang (2003) [19]	UNEP [20]
Max	7816	Monte Carlo simulation ($n = 10{,}000$)	179.264	Measured data ($n = 19$)	13.6 (No control) 6.11 (Bag filter) Measured data ($n = 2$)	90 (No control)[a] 10 (Medium control)[a] 0.4 (Optimal control)[a] Various data reference (not explicitly stated)
Min	1.490×10^{-08}		0.131			
Average	39.920		27.888			
Median	0.986	CDF median value in Pareto distribution ($n = 10{,}000$)	19.294	Arithmetic median value ($n = 19$)		

Unit: Dioxins Emission(μg I-TEQ)/Cremation

[a] No control (Class1): combustion temp. < 850 °C, no flue gas cleaning system, treated wood coffin

Medium control (Class2): combustion temp. ≥ 850 °C, only De Dust system, non-treated wood coffin

Optimal control (Class3): combustion temp. ≥ 850 °C, air pollution control system, non-treated wood coffin

domestic and international research related to the calculation of dioxin emission factors for cremation facilities. Yu (2008) calculated the emission factor for 19 cremation facilities in South Korea and the emission factor of PCDDs/Fs was calculated as 27.888 μg I-TEQ/Cremation by calculating the arithmetic mean value of calculated based on domestic field measurement."

Wang (2003) calculated dioxin emission factors for two cremation facilities in Taiwan and the emission factors for cremation facilities without prevention facilities and cremation facilities with bag filters were 13.6 and 6.11 μg I-TEQ/Cremation (11% oxygen Conc. correction, respectively).

United Nations Environment Programme (UNEP) presents emission factors for each class according to the level of air pollution control by cremation facility and the emission factors for each class are Class1 (No control) 90 μg I-TEQ/Cremation, Class2 (Medium control) 10 μg I-TEQ/Cremation, Class 3 (Optimal control) was presented as 0.4 μg I-TEQ/Cremation.

As a result of comparison with the UNEP emission factor, the emission factor value of 0.986 μg I-TEQ/Cremation presented in this study was found to be relatively higher than the emission factor of 0.4 μg I-TEQ/Cremation of Class 3. This difference is because the probability distribution of the emission factor in this study was selected as the Pareto distribution. However, it was influenced by the median value selection to represent the entire emission factor. If this is compared with the lower 20% value of 0.248 μg I-TEQ/Cremation, the Pareto cutoff value, a lower emission factor value than Class 3 can be confirmed. As a result of comparison with UNEP's emission factor, most cremation facilities in Korea operate under optimal conditions such as combustion conditions, proper operation of prevention facilities and input material management. However, some facilities require additional management for proper dioxin emissions from exhaust gases.

Conclusion

This study confirmed the concentration status of cremation facilities in South Korea. The concentration of dioxin in the 23 cremation facilities surveyed ranged from 0.001 to 4.440 ng I-TEQ/Sm^3 which is the actual concentration that is not corrected with the standard oxygen concentration. It was confirmed that there were differences in the composition of prevention facilities in the crematorium facilities in this study and there were limitations in confirming the difference in dioxin concentration according to the composition of prevention facilities due to the lack of observations.

Korea's Residual Pollutant Control Act does not manage dioxin emissions from cremation facilities. Therefore, if legal management is implemented, systematic and efficient management of dioxin concentrations will be possible in cremation facilities.

In this study, as a result of calculating the dioxin emission factor of cremation facilities through a Monte Carlo simulation, the representative emission factor value was 0.986 I-TEQ/Cremation and the 95% confidence interval was in the range of 0.026–36.216 μg I-TEQ/Cremation.

The probability density distribution of the emission factors of creative facilities in South Korea was predicted using the Pareto distribution. The Pareto distribution states that 80% of a phenomenon's effects are caused by 20%. In this study, the emission factor value which is a cumulative probability density of 80% corresponding to the Pareto Cutoff was calculated as 5.824 μg I-TEQ/Cremation, which means that the emission factor value below 5.824 μg I-TEQ/Cremation is the majority of all the emission factors.

This study suggests a research method for estimating the emission factors from data corresponding to a non-normal distribution, which will be used in future studies to calculate the emission factors of various environmental pollutants. In addition, it is expected to be used as basic data for future cremation facility installation expansion policy establishment, cremation facility design standard setting, environmental impact assessment and improvement of existing facilities.

Data availability The dataset used in this study are available upon request from the corresponding author.

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