



Article

Major Elements to Consider in Developing Ammonia Emission Factor at Municipal Solid Waste (MSW) Incinerators

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Abstract: NH₃ is one of the major substances contributing to the secondary generation of PM_{2.5}; therefore, management is required. In Korea, the management of NH₃ is insufficient, and the emission factor used by EPA is the same as the one used when calculating emissions. In particular, waste incineration facilities do not currently calculate NH₃ emissions. In the case of combustion facilities, the main ammonia emission source is the De-NO_x facility, and, in the case of a power plant with a De-NO_x facility, NH₃ emission is calculated. Therefore, in the case of a Municipal Solid Waste (MSW) incinerator with the same facility installed, it is necessary to calculate NH₃ emissions. In this study, the necessity of developing NH₃ emission factors for an MSW incinerator and calculating emission was analyzed. In addition, elements to be considered when developing emission factors were analyzed. The study found that the NH₃ emission factors for each MSW incinerator technology were calculated as Stoker 0.010 NH₃ kg/ton and Fluidized Beds 0.004 NH₃ kg/ton, which was greater than the NH₃ emission factor 0.003 NH₃ kg/ton for the MSW incinerator presented in EMEP/EEA (2016). As a result, it was able to identify the need for the development of NH₃ emission factors in MSW incinerators in Korea. In addition, the statistical analysis of the difference between the incineration technology of MSW and the NH₃ emission factor by the De-NO_x facility showed a difference in terms of both incineration technology and De-NO_x facilities, indicating that they should be considered together when developing the emission factor. In addition to MSW, it is believed that it will be necessary to review the development of emission factors for waste at workplaces and incineration facilities of sewage sludge.

Keywords: PM_{2.5} secondary sources; municipal solid waste; De-NO_x facilities; incinerator type; ammonia emission factor



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1. Introduction

Ammonia (NH₃) is a significant contributor to climate change and air pollution. Its negative radiative forcing plays a role in climate change, whereas its contribution to the secondary formation of PM_{2.5} has emerged as a source of air pollution [1–3]. South Korea is making conscious efforts to reduce the emission of ultrafine particles by managing secondary products, which are one of the major causes of the increase in the concentration of ultrafine particles. In South Korea, NO_x (nitrogen oxides) and SO_x (sulfur oxides), which are secondary products of ultrafine particles, are being monitored and managed in real-time [4–6]. However, when calculating NH₃ emissions, the emission factors suggested by the U.S. Environmental Protection Agency (EPA) and CORINAIR in Europe are used, and there are many unknown sources of omissions [7–9]. Therefore, NH₃ emissions do not reflect the characteristics of Korea, and the emission factor values of other countries are used as they are, so the reliability of emissions is low. Systematic management of PM_{2.5} requires improving the reliability of the inventory's ability to identify emissions, and NH₃, one of the secondary generating substances, should improve the reliability of the

emission inventory by developing emission factors and calculating emissions that reflect the characteristics of the country.

In the case of stationary combustion facilities among the NH_3 emission sources dealt with in Korea, selective catalytic reduction (SCR) and selective noncatalytic reduction (SNCR) are used to reduce NO_x , an air pollutant. SCR and SNCR are a method of reducing NO_x using NH_3 . If NH_3 is used excessively to reduce NO_x , slip may occur, which causes NH_3 to be discharged from the final stack [10–13]. Unlike NO_x and SO_x , which are the main elements emitted by fuel combustion, NH_3 reacts using NH_3 as a reducing agent to reduce NO_x , and the remaining substances are discharged. Therefore, NH_3 emission from stationary combustion facilities is characterized by base on the slip, unlike other air pollutants emitted by fuel combustion.

Korea calculates NH_3 emissions mainly from boilers used in power generation facilities and businesses among fixed combustion facilities. However, waste incineration facilities are equally equipped with De- NO_x facilities to reduce NO_x , but NH_3 emissions are not calculated when calculating national air pollutant emissions.

Waste incineration facilities use various types of incinerators to dispose of waste, and each type of incineration uses De- NO_x facilities to reduce NO_x . Combustion efficiency and method may vary depending on the type of incineration. In the case of greenhouse gases N_2O (nitrous oxide) and CH_4 (methane), among the components emitted in relation to combustion, emission factors are developed and divided by waste incinerator type [14]. For NO_x , it is determined that incineration types need to be considered to ensure the reliability of the inventory, as they are discharged due to fuel combustion, and the associated NH_3 needs to be considered as well. Therefore, in this study, we would like to check whether incineration type should be considered when developing NH_3 emission factors.

In addition, in the case of fuel combustion facilities such as power plants, the boiler type is not considered, but emission factors are separately calculated and presented in consideration of SCR and SNCR, which are De- NO_x facilities. Therefore, in this study, even when developing the NH_3 emission factor for municipal solid waste, we would like to check whether the emission factor for each De- NO_x facility should be developed separately. When developing emission factors for incineration type and De- NO_x facilities, the elements to consider were evaluated by estimating each NH_3 emission factor and analyzing whether there was a statistical difference.

2. Materials and Methods

2.1. Selection of Objective Facilities

This study was intended to calculate the NH_3 emission factor for different incinerator types and De- NO_x facilities to identify the need to consider these parameters when developing the NH_3 emission factor for MSW incineration facilities. For the NH_3 concentration analysis, 515 samples were collected and analyzed. The classification of incinerator types and De- NO_x facilities is shown in Table 1. The stoker and fluidized bed combustion type of incinerators were considered and SCR and SNCR were selected for the De- NO_x facilities. In South Korea, the stoker type of incinerator is widely used for MSW incineration. Therefore, in this study, the NH_3 emission factor was calculated using 476 analysis data from the stoker type incineration facilities. Additionally, the fluidized bed combustion type, which is the second most widely used incinerator type, was selected for comparing the emission factors with those of other incinerator types. To calculate the NH_3 emission factor for the fluidized bed combustion type, 39 samples were analyzed.

2.2. NH_3 Concentration Analysis

The samples were collected according to the process test method proposed by South Korea for NH_3 emission concentration measurement, and the indophenol method was selected for sample collection from among the methods proposed in the process test method (odor process test method, air pollution process test method) [15,16]. Indophenol method measures the absorbance of the indophenol reagents that are produced by adding sodium

hypochlorite solution and phenol or sodium nitroprusside solution into the sample solution. The reagents react with the ammonium ions in the sample solution and the amount of NH_3 released is calculated [17]. The NH_3 sample was prepared from NH_3 absorbent solution (absorbed using 50 mL boric acid solution), which was taken in two 50 mL volumetric flasks, and exhaust fumes from 80 L solution were absorbed for approximately 20 min at a rate of 4 L/min using a pump [18]. As NH_3 dissipates in the presence of moisture, moisture level should be controlled to minimize its effect. Furthermore, high moisture levels occur in exhaust fumes generated by waste combustion; thus, this moisture should also be eliminated prior to NH_3 sample collection. Therefore, in this study, a moisture absorption bottle containing silica gel was installed in front of the sample collection apparatus for moisture removal. The NH_3 sample was collected based on the schematic diagram shown in Figure 1. The NH_3 concentration in the sample solution was estimated by measuring the absorbance of the absorbent solution using the spectrophotometer at a wavelength of 640 nm.

Table 1. Sampling status of objective facilities.

Waste Type	Incinerator Type	De-NOx Facilities	Sampling
MSW (Municipal Solid Waste)	Stoker	SCR	337
		SNCR	139
		Total	476
	Fluidized bed	SCR	19
		SNCR	20
		Total	39
		Total	515

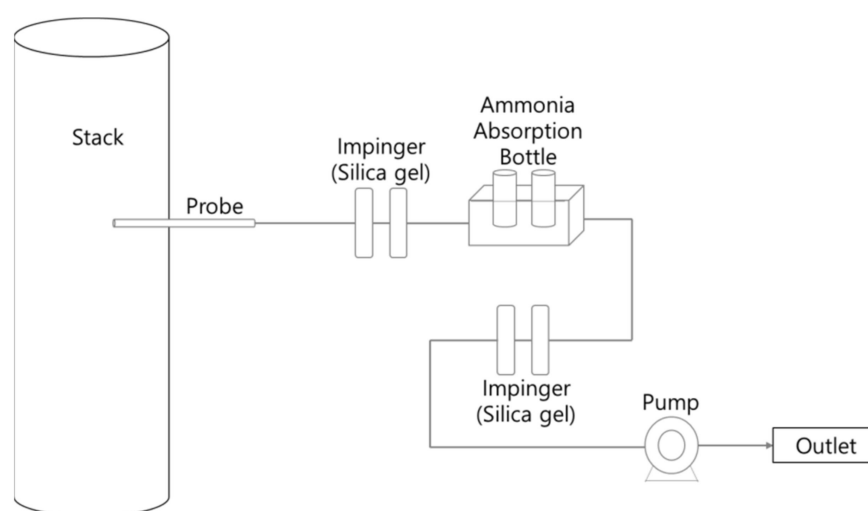


Figure 1. Schematic of the field setup for ammonia sampling at MSW incinerator.

2.3. Development of the NH_3 Emission Factor

The equation used in the previous studies for calculating the NH_3 emission factor was referred to in the present study and the method used has been outlined in Equation (1) [19,20]. To estimate the NH_3 emission factor of the MSW incineration facility, information on the NH_3 concentration, flow rate, and the amount of waste incinerated are necessary. CleanSYS data were acquired from the target workplace and the daily-accumulated flow rate was used to collect data on the flow rate. CleanSYS is presently being utilized for managing the air pollution in South Korea. CleanSYS measures and man-

ages the flow rate of SO_x, particulate matter (PM), and NO_x, and measures the temperature of exhaust fumes and the concentration of air pollutants in real-time. However, it does not measure NH₃ at present [21]. The data obtained from the target workplace were used to measure the amount of waste incinerated

$$EF_{NH_3} = \left[C_{NH_3} \times \frac{M_w}{V_m} \times Q_{day} \times 10^{-6} \right] / FC_{day} \quad (1)$$

where EF is emission factor (kg NH₃/ton); C_{NH_3} is NH₃ concentration in exhaust gas (ppm); M_w is molecular weight of NH₃ (constant) = 17.031 (g/mol); V_m is one mole ideal gas volume in standardized condition (constant) = 22.4 (10⁻³ m³/mol); Q_{day} is daily accumulated flow rate (Sm³/day) (based on dry combustion gas); and FC_{day} is daily waste incineration (ton/day).

2.4. Statistical Analysis for the Incinerator Types and De-NO_x Facilities

In this study, the average distribution of the NH₃ emission factor of different types of pollution prevention facilities and incinerator types of an incineration facility was compared to investigate whether the pollution prevention facility type and incinerator type of an MSW incineration facility affect the NH₃ emission factor. SPSS 21 program (IBM, USA) De-NO_x was used for statistical analysis; the statistical approach for analyzing the NH₃ emission factor difference due to the pollution prevention facility type and incinerator type of an incineration facility is presented in Figure 2.

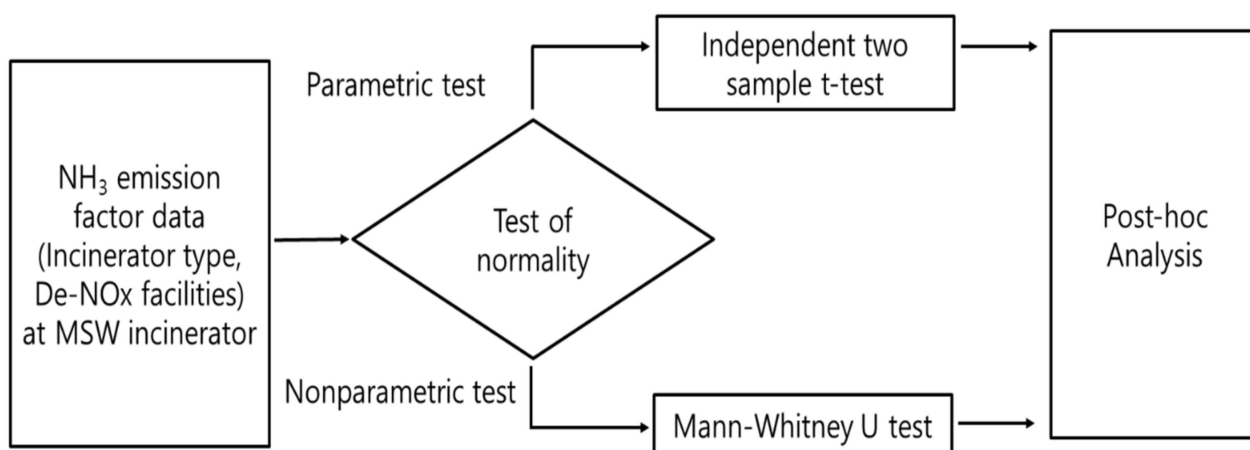


Figure 2. Schematic of statistics analysis.

3. Results and Discussion

3.1. NH₃ Emission Factor of the MSW Incineration Facility

3.1.1. NH₃ Emission Factor of Different Incinerator Types of the MSW Incineration Facility

To investigate the elements influencing the NH₃ emission factor with respect to different incinerator types, the NH₃ emission factor for each incinerator type was calculated, and the results are provided in Table 2. The NH₃ emission factor of the stoker type was 0.010 kg NH₃/ton with a standard deviation of 0.009 kgNH₃/ton, while that of the fluidized bed type was 0.004 kg NH₃/ton, with a standard deviation of 0.004 kg NH₃/ton. The standard deviation of both stoker and fluidized beds was similar to or greater than the average emission factor. This difference is lower than the 95% confidence interval of 0.005–0.018 kgNH₃/ton of NH₃ emission factor for municipal solid waste, suggested by EMEP/EEA (2016), a previous study. Therefore, it was confirmed that the standard deviation of this study was lower than that of previous studies.

Table 2. NH₃ emission factor of MSW incinerator type

Waste Type	Incinerator Type	This Study (NH ₃ kg/ton)	SD	Sampling	Kang et al. (2020) [13] (NH ₃ kg/ton)	EMEP/ EEA (2016) [8] (NH ₃ kg/ton)
MSW	Stoker	0.010	0.009	476	0.009	0.003
	Fluidized bed	0.004	0.004	39	-	

In the case of a fluidized bed boiler, the gas temperature is lower than that of the stoker type and the amount of excess air is low, so less NO_x is discharged. When less NO_x is emitted, the amount of NH₃ used to reduce NO_x decreases. Therefore, it is judged that the ammonia emission factor is lower in the fluidized bed type than in the stoker type because there is not much NH₃ discharged due to slip [22,23].

The results of the NH₃ emission factors for MSWs from previous studies were compared with the results of this study. The NH₃ emission factor of the stoker type was 0.010 kg NH₃/ton, which was higher than that (0.009 kg NH₃/ton) calculated by Kang et al. (2020) and that stated by the European Monitoring and Evaluation Programme (EMEP)/European Environment Agency (EEA) (0.003 kgNH₃/ton). In the case of the Stoker incinerator, the difference in NH₃ emission factors estimated in the study of Korean facilities was found to be smaller than that of EMEP/EEA in Europe, so it is necessary to develop NH₃ emission factors that reflect national characteristics. The NH₃ emission factor of the fluidized bed type was 0.004 kgNH₃/ton, which was lower than the value acquired by Kang et al. (2020) and higher than that proposed by EMEP/EEA. Therefore, it could be confirmed that, in the case of fluidized-bed incineration, emission factors need to be developed, because they were calculated to be higher than the NH₃ emission factors used in Europe.

3.1.2. NH₃ Emission Factor of De-NO_x Facilities of the MSW Incineration Facility

To investigate the effect of the NH₃ emission factor with different De-NO_x facilities, the NH₃ emission factor for each De-NO_x facility was calculated; the results are shown in Table 3.

Table 3. NH₃ emission factor of De-NO_x facilities for MSW incinerator type

Waste Type	Incinerator Type	De-NO _x Facilities	This Study (NH ₃ kg/ton)	SD	Sampling
MSW	Stoker	SCR	0.010	0.008	337
		SNCR	0.011	0.010	139
	Fluidized bed	SCR	0.002	0.0004	19
		SNCR	0.006	0.0046	20

The NH₃ emission factor of the SCR facility from among the stoker type of incinerators was 0.010 kgNH₃/ton, with a standard deviation of 0.008 kg NH₃/ton, while that of the SNCR facility was 0.011 kg NH₃/ton, with a standard deviation of 0.010 kg NH₃/ton. The NH₃ emission factor of the SCR facility with fluidized bed type was 0.002 kgNH₃/ton, with a standard deviation of 0.0004 kgNH₃/ton, while that of the SNCR facility was 0.006 kgNH₃/ton, with a standard deviation of 0.0046 kgNH₃/ton, indicating that the NH₃ emission factor of the SCR facility was lower than that of the SNCR facility. In the case of the standard deviation of the De-NO_x facility, it was found that all the standard deviations of SNCR were larger than that of SCR. This is because SCR has a separate facility and injects ammonia through a nozzle, whereas SNCR is installed in the boiler itself, so it is considered that the deviation is relatively large due to the influence of the environment during the combustion of the boiler [24,25]. The deviation between SCR and SNCR was also found to be lower than the difference between MSW suggested by EMEP/EEA (2016).

This difference is similar to the difference in NH_3 emission factors for each De- NO_x facility of a power plant among fixed combustion facilities proposed by EPA. EPA showed that the NH_3 emission factor of SCR was higher than that of SNCR [26]. Therefore, it was found that the difference in NH_3 emission factor according to the De- NO_x facility in this study was significant.

3.2. Normality Tests for the NH_3 Emission Factor of the MSW Incineration Facility

Prior to analyzing the measured NH_3 emission factors statistically, the normality of the data should be examined. Kolmogorov–Smirnov (KS) test, Q-Q plot, chi-square test, and Shapiro–Wilk test are some of the commonly used normality tests. In particular, the Shapiro–Wilk and KS tests are applied based on the size of the population. The KS test is used when the population size is greater than 2000, whereas the Shapiro–Wilk test is used when the population size is less than 2000. These normality tests examine the normality and non-parametric using significance probability. They assume the null hypothesis that the distribution is normal when the significance probability is higher than 0.05, whereas it switches to non-parametric by rejecting the null hypothesis when the significance probability is lower than 0.05.

3.2.1. Normality Test for the NH_3 Emission Factor for Incinerator Type of the MSW Incineration Facility

To determine whether the incinerator type of the MSW incineration facility should be considered during the NH_3 emission factor development, the normality of the NH_3 emission factor data for each waste incinerator type was examined using the SPSS 21 statistics program before analysis. As the number of samples for the NH_3 emission factor for each waste incinerator type were lower than 2000, Shapiro–Wilk normality test was used. As a result of the review of previous studies, data related to the concentration of gaseous matter emitted from waste incineration facilities in previous studies related to waste and incineration facilities appeared mainly as nonparametric patterns. In the case of the emission factor calculated in this study, it was confirmed that the emission factor was also non-parametric and appeared similar to the previous studies [27,28].

Based on the normality tests, both the Stoker type and fluidized bed type used for the MSW incineration showed a significance probability of less than 0.05 (Table 4). Thus, they were not normally distributed [22,23].

Table 4. The result of normality test NH_3 emission factor data of incinerator type at MSW incinerator.

Normality Test Result	Shapiro-Wilk		
	Statistic	Degree of Freedom, Df	Sig.
Stoker	0.849	476	<0.001
Fluidized bed	0.732	39	<0.001

3.2.2. Normality Test for the NH_3 Emission Factor of De- NO_x Facilities of the MSW Incineration Facility

For the De- NO_x waste incineration facilities, the normality of the data of the NH_3 emission factor was examined. Since the number of samples for the NH_3 emission factor of the De- NO_x waste facilities were lower than 2000, Shapiro–Wilk test was used to examine the normality.

Based on the normality test results, the data for the Stoker incinerator type used for MSW incineration showed a significance probability below 0.05, indicating that the data were not normally distributed (Table 5). Additionally, the significance probability for the data of the fluidized bed type was also lower than 0.05, confirming that the data were not normally distributed. If the sample size is less than 30, the number of samples required for the central limit theorem will not be met, even though it is proven to be normally

distributed through the normality test results, and thus normal distribution cannot be defined and non-parametric tests should be used [29,30].

Table 5. The result of normality test NH_3 emission factor data of De- NO_x facilities for MSW incinerator type.

		Shapiro-Wilk		
		Statistic	Degree of Freedom, Df	Sig.
Stoker	SCR	0.862	337	<0.001
	SNCR	0.817	139	<0.001
Fluidized bed	SCR	0.972	19	0.808
	SNCR	0.909	20	0.062

3.3. Mann–Whitney U Test of NH_3 Emission Factor for Incinerator Type and De- NO_x Facilities

3.3.1. Mann–Whitney U Test for the NH_3 Emission Factor for Incinerator Type of the MSW Incineration Facility

As the NH_3 emission factor for different incinerator types of MSW incineration facility did not follow a normal distribution, the comparison between the incinerator types was performed using the Mann–Whitney U test, a non-parametric significance test (Table 6). The Mann–Whitney U test results revealed that the significance probability was less than 0.05, suggesting that the null hypothesis of “ NH_3 emission factors for different incinerator types do not show a significant difference” can be rejected. Therefore, the difference in the NH_3 emission factors depending on different incinerator types was statistically significant. Hence, the emission factors for each incinerator type need to be developed.

Table 6. The result of Mann–Whitney U test by NH_3 emission factor for MSW incinerator type.

Incinerator Type	Mean \pm SD	Z	P-Value
Stoker	0.010 \pm 0.009	−5.763	<0.001
Fluidized bed	0.004 \pm 0.004		

3.3.2. Mann–Whitney U test for the NH_3 Emission Factors for De- NO_x Facilities of the MSW Incineration Facility

The De- NO_x facilities for different incinerator types of the MSW incineration facility did not follow normal distribution based on the normality test results. Therefore, the differences in the NH_3 emission factors depending on the different De- NO_x facilities were analyzed using the Mann–Whitney U test; the results are shown in Table 7.

Table 7. The Result of Mann–Whitney U Test by NH_3 Emission Factor of De- NO_x Facilities for MSW Incinerator Type.

Incinerator Type		Mean \pm SD	Z	P-Value
Stoker	SCR	0.010 \pm 0.008	−1.995	0.046
	SNCR	0.011 \pm 0.010		
Fluidized bed	SCR	0.002 \pm 0.0004	−3.737	<0.001
	SNCR	0.006 \pm 0.0046		

The Mann–Whitney U test results show that the significance probability was less than 0.05, rejecting the null hypothesis, which stated that the NH_3 emission factors for different De- NO_x facilities for each incinerator type do not show a significant difference. Therefore, the NH_3 emission factors depending on the De- NO_x facilities for each incinerator type

of the MSW incineration facility should be considered, and development of the emission factor is necessary.

4. Conclusions

NH₃ emissions need to be controlled efficiently, as NH₃ is a major contributor to climate change and air pollution. However, in South Korea, emission factors abroad are being applied for the calculation of NH₃ emissions. In particular, the SCR and SNCR facilities from among the stationary combustion facilities are being utilized in the power plant and workplace combustion facilities, and thus the NH₃ emission factor of each fuel needs to be calculated. However, waste incineration facilities use the same facilities but do not calculate NH₃ emissions. In the waste sector, only ammonia discharged from the wastewater treatment process is currently calculated as a pollutant source [7]. Therefore, development of the NH₃ emission factor for waste incineration facilities is necessary.

In this study, we investigated the necessity of considering the incinerator type and De-NO_x facilities while developing the NH₃ emission factor for MSW incineration facilities. The NH₃ concentration of 515 samples acquired from the MSW incineration facility was analyzed and the subsequent NH₃ emission factors for different incinerator types and De-NO_x facilities were calculated.

Based on the analysis results, the NH₃ emission factor of the SCR facility among the Stoker type was 0.010 kgNH₃/ton, with a standard deviation of 0.008 kgNH₃/ton, while that of the SNCR facility was 0.011 kgNH₃/ton, with a standard deviation of 0.010 kgNH₃/ton. In terms of the incineration type, the NH₃ emission factor of the SCR facility with the fluidized bed type was 0.002 kgNH₃/ton, with a standard deviation of 0.0004 kgNH₃/ton, while it was 0.006 kgNH₃/ton, with a standard deviation of 0.004 kgNH₃/ton of the SNCR facility. This indicated that the NH₃ emission factor of the SCR facility was relatively lower than that of the SNCR facility. The comparison of the emission factors of South Korea with that of other countries, the differences in the emission factors estimated for South Korea were smaller than those proposed by other countries. This suggests that there is a need to develop and apply the NH₃ emission factor considering the South Korean national standards.

The statistical results for comparison of differences confirmed that the NH₃ emission factor of De-NO_x facilities for each incinerator type was non-parametric, and hence the Mann–Whitney U test was applied. The result of the statistic, the null hypothesis, which stated that emission factors of each facility were not significantly different, was rejected. Thus, the incinerator type and De-NO_x facilities should be considered for the development of the NH₃ emission factor.

In this study, the incineration type and NH₃ emission factor of De-NO_x facilities were calculated for urban solid waste incineration facilities, and the necessity and consideration of the emission factor development were identified, respectively. What could be confirmed by this study and its meaning are as follows:

1. The necessity of developing emission factors reflecting national characteristics was confirmed by suggesting that the difference between the NH₃ emission factors calculated in Korea is less than the difference between the NH₃ emission factors suggested in Europe;
2. NH₃ emission factor according to the incineration type and De-NO_x facility of the municipal solid waste incineration facility was presented for reference;
3. In relation to NH₃ discharged from municipal solid waste incineration facilities, the need to consider this when developing emission factors was evaluated by statistically analyzing differences according to incineration types and De-NO_x facilities. Therefore, if whether other air pollutants also affect the incineration type is checked, the reliability of the inventory can be improved, and a statistical analysis procedure is also presented, so it can be referred to in related studies;
4. In Korea, NH₃ emissions are not calculated from waste incineration facilities. In this study, NH₃ is also emitted from waste incineration facilities through the research

results, and the necessity of calculating the emission is also presented by comparing it with overseas emission factors.

In the future, if research calculating the NH₃ emission factors for workplace waste and sewage sludge incineration facilities, such as those classified in greenhouse gases other than urban solid waste, is carried out, it is believed that the reliability of the NH₃ inventory in the waste sector can be improved. Additionally, emission factors of the pyrolysis melting facility that were not analyzed in this study can be investigated in the future.

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