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Ammonia Emission Estimation of Biogas Production Facilities in South Korea: Consideration of the Emission Factor Development

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Abstract: This study identified the need to develop ammonia (NH_3) emission factors for biogas production facilities in Korea and examined the base unit that should be considered when developing emission factors. The analysis showed that the ammonia concentration of three biogas production facilities ranged from approximately 0.04 to 8 ppm. The NH_3 emission factors were found to be 0.005 kg NH_3 ton-waste and 0.150 kg $NH_3/10^{-3}$ Nm^3-biogas. The estimated emission factors were also used to calculate the total emissions, which were found to be small. The uncertainty of the emission factors ranged from approximately −5% to +8% for the waste-based emission factors and approximately −5% to +7% for the biogas-based emission factors. Although the uncertainty of the emission factor differences is not large, it is low compared to the international emission factor uncertainty (maximum 191%, minimum −40.7%). Considering the development of waste-based and biogas-based emission factors, there is not much difference in terms of uncertainty of emission factors, so it is judged that it will be easier to develop emission factors based on biogas production in terms of securing and managing overall data.

Keywords: waste inventory sector; biogas production facility; ammonia emission; emission factors

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1. Introduction

The fine particulate matter concentration in South Korea was 19.1 μg/m^3 in 2021, which was higher than the annual average of 5 μg/m^3 of fine particulate matter recommended by the World Health Organization (WHO) [1]. Furthermore, this value surpassed the annual average atmospheric environment standard of 15 μg/m^3 in South Korea [2]. Therefore, the effective management of fine particulate matter remains a significant area of concern.

Fine particulate matter is significantly affected by precursor pollutants that intervene in the secondary generation. In South Korea, 72% of fine particulate matter is derived from precursors, which are known to be NO_x, ammonia (NH_3), and volatile organic compounds (VOCs) [3,4].

In South Korea, fine particulate matter mitigation policies consider many aspects, but the management of precursor pollutants is only focused on nitrogen oxide (NO_x)and sulfur oxides (SO_x) [5,6]. In the case of NH_3, management through the development of national emission factors and real-time measurement is challenging. Currently, there is a significant omission of NH_3 emissions due to the lack of data on its activity and associated emission factors. Therefore, the management of fine particulate matter must involve safeguarding the reliability of NH_3 emissions and relevant inventories in addition to the well-managed precursor pollutants.

The waste sector among NH_3 emissions only determines the emissions from sources related to wastewater, thereby resulting in a relatively low NH_3 emissions rate, compared to the total emissions. In contrast, other countries include NH_3 emissions from biogas production facilities and landfills in their waste sector emission assessment, which is not the case in South Korea. Regarding biogas production facilities, even in overseas countries, studies have been conducted on whether increasing biogas production or reducing NH_3 or the greenhouse gas CH_4 or related substances affects biogas production, rather than developing NH_3 emission factors used for national emission calculations [7–9]. However, in the case of Korea, it is difficult to estimate biogas emissions due to the lack of NH3 emission factors. Therefore, it is necessary to develop emission factors before research related to increasing biogas production.

Overseas emissions account for the NH_3 emissions from biogas production facilities, which are categorized under the waste sector, into their assessment by developing the emissions factor based on nitrogen content. Since NH_3 emissions from biogas are missing in the Korean case, it is necessary to confirm whether it is emitted or not, and to consider whether it is possible to develop an emission factor based on nitrogen as in overseas countries, or whether other factors should be considered. In the case of biogas production facilities in Korea, most of the biogas produced is used as fuel for the facility. In addition, since biogas storage tanks are sealed, NH_3 generated in biogas production facilities is treated by cleaning or combustion to deodorize odors after drying facilities to produce biogas.

Therefore, this study aims to identify NH_3 emissions from the post-drying process of biogas production facilities in Korea and to approach the need to develop an emission factor. In addition, the reference unit was considered as one of the factors required to develop an emission factor, and an uncertainty analysis was performed to increase the reliability of the determined emission factor.

2. Materials and Methods

2.1. Selection of Objective Facilities

This study considers the types of waste processed in South Korean biogas production facilities in to measure the NH_3 concentration and determine the emission factors of three facilities. The daily biogas production in the target facilities is 30,000 Nm^3 or above, and the samples were processed for 2–4 years for each facility. From each facility, 30 samples were collected to measure the NH_3 concentration. The contents related to the facilities are summarized in Table 1.

Table 1. Characteristics of the investigated biogas production facilities.

Site	Waste Type	Biogas Production (Nm^3/Day)	Waste Throughput (Tons/Day)	Sampling
A biogas production facility	Livestock manure, food waste mixing	5976	123	31
B biogas production facility	Food waste	3042	122	122
C biogas production facility	Sewage sludge	7080	114	84

2.2. Ammonia Analysis at Biogas Production Facilitys

In this study, the indophenol method proposed by the "Official Methods to Test Malodor" and "Official Methods to Test Air Pollution" of South Korea was referenced to measure the concentration of NH_3 emission in biogas facilities [10,11]. The indophenol method measures the ammonia concentration by adding the sodium hypochlorite solution and the phenol-sodium nitroprusside solution to the sample solution and using the absorbance of the indophenol produced by the reaction with ammonium ions.

The sample extraction for ammonium concentration measurement uses a mini pump (SIBATA MP-ΣNII, Saitama, Japan) by adding 25 mL of boric acid solution as ammonium absorbent in two 50 mL flasks. Furthermore, 50 L exhaust gas was introduced for 12 min

30 s at 4 L/min. External emissions of NH_3 from biogas production facilities in Korea occur during the deodorization process after drying and pretreatment of inputs. Most facilities use scrubbers, but some facilities use a regenerative thermal oxidizer (RTO) as part of the odor treatment process. Two of the facilities in this study use a wet scrubber system and one uses an RTO, and this study measured the final ammonia emissions from the scrubber system and the stack after the RTO. Ammonia sample collection proceeded as shown in Figure 1. The ammonia concentration was determined from the absorbance of the captured solution, which was analyzed at a wavelength of 640 nm using a spectrophotometer (Shimadzu 17A, Kyoto, Japan).

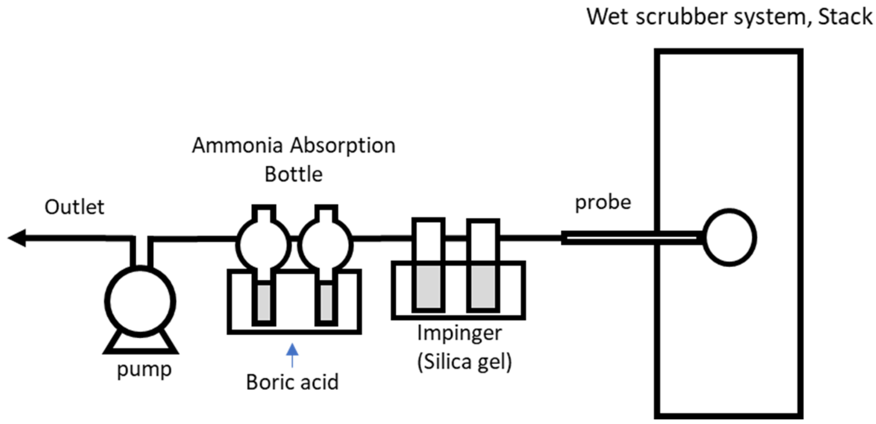

Figure 1. Sample Collection Schematic for Ammonia Concentration Analysis.

2.3. Ammonia Emission Factor Development Considerations at Biogas Production Facility

The emission factor of air pollutants refers to the emission of air pollutants according to unit activity data, i.e., the emission factor of air pollutants in the fuel combustion sector, refers to the emission of air pollutants per unit of fuel burned, and in the case of the production of a substance, the emission of air pollutants per unit of product production is an example.

Based on the meaning of emission factors, there are two options for biogas production facilities. On the one hand, biogas production facilities. utilize waste to produce biogas, so a waste-based emission factor can be developed. On the other hand, since biogas production facilities produce biogas, it would be possible to develop an emission factor based on the production of biogas, i.e., a material like that produced in general manufacturing. However, in other countries, NH_3 emission factors related to biogas production are based on ammonia nitrogen. The source units that may be considered when developing NH_3 emission factors for Korea biogas production facilities are shown in Table 2.

Table 2. Calculation criteria for developing NH_3 emission factors for Biogas production facilities.

Classification	Unit	Description
N-base	$kgNH_3$-N/N in feedstock	Emission factors are calculated based on NH_3-N ammonia nitrogen per unit of raw material input
Waste base	$kgNH_3$/tons-waste	Calculate emission factors based on the amount of waste (food, animal manure, sewage sludge) processed
Biogas production base	$kgNH_3/10^3$ m^3-biogas	Calculated emission factor based on biogas production.

In this study, we reviewed the units that can be considered for the development of NH_3 emission factors for biogas production facilities in the Korean context.

First, developing emission factors with N-base has the advantage of being able to compare with emission factors related to currently developed overseas biogas production facilities, but it is difficult to reflect these characteristics because ammonia nitrogen is not currently analyzed in Korea, and the types of wastes utilized for biogas production are diverse and in some cases are mixed. In addition, it is difficult to secure continuous activity data. Therefore, it was excluded from the development of emission factors in this study.

Secondly, the method based on the waste used for biogas production has the advantage of having activity data that can be utilized because the amount of waste disposal related to biogas production is currently collected in Korea. However, with this method, it is difficult to compare similar emission factors developed overseas, and it is a little difficult to consider such a ratio because there are various types of waste used in biogas production, and some are mixed.

Finally, in the case of biogas production, it can be utilized as an activity data since the production is currently aggregated in Korea, and it has the advantage of being applicable regardless of the type of waste processed, but this method also has the disadvantage that it is difficult to compare with overseas values that have developed emission factors based on ammonia nitrogen.

In this study, we calculated NH_3 emission factors based on waste and biogas production, a method currently applicable in Korea.

2.4. Estimation of Ammonia Emission Factor at Biogas Production Facility

In the case of biogas, the nitrogen content is considered overseas. The present study incorporated both the biogas production and waste processing amount to calculate NH_3 emission factor that accurately reflects the current situation in South Korea.

To estimate the emission factor-based waste, the flowrate and concentration of the discharged pollutants were used to calculate the emissions, and the amount of waste input to produce biogas were considered [12,13]. This research referred to the formula used in previous research to calculate the NH_3 emissions factor based on input waste, as shown in Equation (1) [14]. To develop the NH_3 emissions factor in biogas facilities, the waste processing amount, flowrate was obtained from the facilities, with daily cumulative flowrate data used for the flowrate.

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

where EF is emission factor (kg NH_3/ton-waste); C_{NH_3} is NH_3 concentration in flue gas (ppm); M_w is molecular weight of NH_3 (constant) = 17.031 g/mol; V_m is one mole ideal gas volume in standardized condition (constant) = $22.4 \cdot 10^{-3}$ Nm^3/mol; Q_{day} is daily accumulated flow rate (Nm^3/day) (based on dry combustion gas); and DW_{day} is daily waste processing amount(tons/day).

To estimate the emission factor-based biogas, and the amount of biogas production were considered. This study calculates the NH_3 emission factor based on biogas production, as shown in Equation (2). To develop the NH_3 emissions factor in biogas production facilities, the flowrate and biogas production data were obtained from the facilities, with daily cumulative flowrate data used for the flowrate.

$$EF_{NH_3} = \left[C_{NH_3} \times \frac{M_w}{V_m} \times Q_{day} \times 10^{-6} \right] / DB_{day} \tag{2}$$

where EF is emission factor (kg NH_3/ton-waste); C_{NH_3} is NH_3 concentration in flue gas (ppm); M_w is molecular weight of NH_3 (constant) = 17.031 g/mol; V_m is one mole ideal gas volume in standardized condition (constant) = $22.4 \cdot 10^{-3}$ Nm^3/mol; Q_{day} is daily accumulated flow rate (Nm^3/day) (based on dry combustion gas); and DB_{day} is daily biogas production(Nm^3/day).

2.5. Uncertainty Analysis of NH_3 Emission Factor by Monte Carlo Simulation

In South Korea, the uncertainty of atmospheric pollutants is determined based on the data attribute rating system (DARS) methodology of the Environmental Protection Agency (EPA), which was grounded on expert judgment [15,16]. However, the European Monitoring and Evaluation Program (EMEP)/European Environment Agency (EEA) states that the quantitative uncertainty assessment on emissions factors must be proceeded based on IPCC's 2006 methodology used in greenhouse gases [17]. To evaluate the level of uncertainty in the NH_3 emission factor calculated for biogas production facilities, this study used the Monte Carlo simulation recommended by the Intergovernmental Panel on Climate Change (IPCC) 2006 guideline [18].

The Monte Carlo simulation generates random numbers based on the input variables and designates the probability density function (PDF) to assess the uncertainty, and it is commonly used in the environmental sector to assess the uncertainty [19–21]. The Monte Carlo simulation analysis involves four stages, and the procedure is outlined in Figure 2. The first stage involved selecting the model, which was accomplished by creating the NH_3 emission factor determination work sheet for the biogas production facility. The second stage involved the verification of the PDF of the input variables necessary for developing the emission factor. By verifying the suitability of the data distribution of each input variable, the PDF was selected, and the significance level of 5% was selected for the hypothesis test. The PDF was determined based on the verification results of each input variable, namely NH_3 emissions concentration, exhaust gas flowrate, biogas production, and amount of waste processing required for the development of NH_3 emission factor. In the third stage, the Monte Carlo simulation was executed, where the "Crystal ball" program was used to proceed with random sampling. Lastly, the simulated results were divided into 95% confidence intervals to estimate the uncertainty.

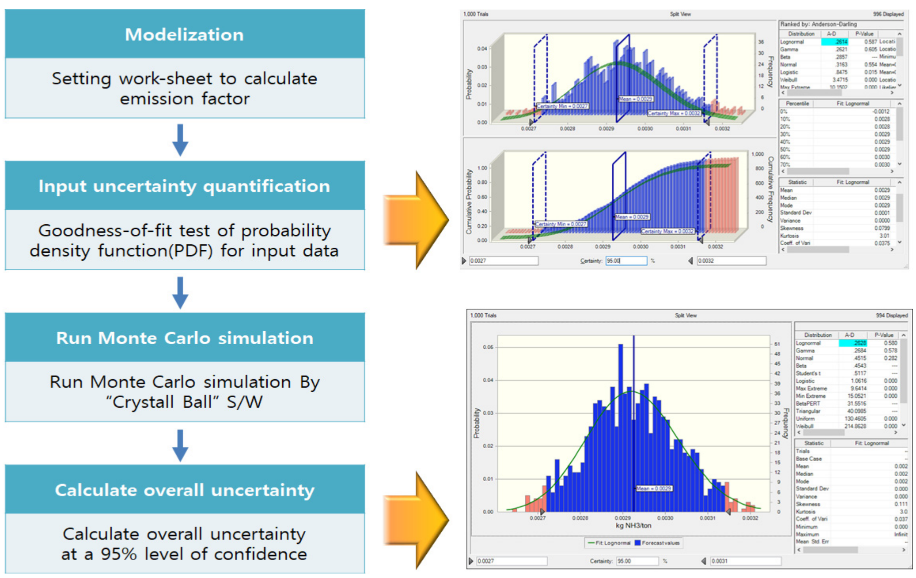

Figure 2. Process of the Monte Carlo Simulation for estimating the uncertainty of the NH_3 emission factor.

3. Results and Discussion

3.1. NH_3 Concentration at Biogas Production Facility by Waste Type

The analysis results of the ammonia concentration in biogas facilities are shown in Table 3. The results showed that the ammonia concentration from biogas facilities was between 0.04–28.47 ppm.

Table 3. NH_3 concentration of the investigated biogas production facilities.

Site	Mean (ppm)	Min (ppm)	Max (ppm)	SD (ppm)	Sampling
A biogas production facility	1.65	0.04	8.80	2.10	31
B biogas production facility	7.99	0.05	29.31	8.95	122
C biogas production facility	2.41	0.04	28.47	4.70	84

The range of ammonia concentration from A biogas production facility was between 0.04–8.80 ppm, and the average concentration was 1.65 ppm. The standard deviation was 2.10 ppm. The range of ammonia concentration from B biogas production facility was between 0.05–29.31 ppm, and the average concentration was 7.99 ppm. The standard deviation was 8.95 ppm. The range of ammonia concentration from C biogas production facility was between 0.04 and 28.47 ppm, and the average concentration was 2.41 ppm. The standard deviation was 4.70 ppm. The reason for such differences was attributed to biogas production facility A using a wet scrubber to manage the air pollutants, biogas production facility C only intermittently using the wet scrubber, and biogas production facility B not using a wet scrubber using a different method of processing.

3.2. Estimate of NH_3 Emission Factor at Biogas Production Facilities

3.2.1. NH_3 Emission Factors Based on Waste Throughput at Biogas Production Facilities

In this study, a total of 237 ammonia samples were collected from three biogas production facilities to determine the NH_3 emission factor, and the results are shown in Table 4. The results show that the NH_3 emission factor of the biogas facility was a total of 0.005 kg NH_3/ton-waste. The NH_3 emission factor for each biogas production facility differed at 0.001 kg NH_3/ton-waste for biogas production facility A, 0.003 kgNH_3/ton-waste for biogas production facility B, and 0.007 kgNH_3/ton-waste for biogas production facility C. The flow at the time of the actual measurement and waste processing amount were considered to have affected the emissions factor rather than the average concentration. Therefore, when managing ammonia emissions, it is necessary to also account for the emissions rather than only the concentration standard. In the case of South Korea, both concentration and emission standards are implemented to regulate air pollutants.

Table 4. NH_3 emission factor based on the waste of the investigated biogas production facilities.

Site	Mean (kgNH_3/Tons-Waste)	SD (kgNH_3/Tons-Waste)	Sampling
A biogas production facility	0.001	0.001	31
B biogas production facility	0.003	0.004	122
C biogas production facility	0.007	0.013	84
Total	0.005	0.009	237

Flow at the time of the actual measurement and waste processing amount were considered to have affected the emissions factor rather than the average concentration. Therefore, when managing ammonia emissions, it is necessary to also account for the emissions rather than only the concentration standard. In the case of South Korea, both concentration and emission standards are implemented to regulate air pollutants.

As mentioned earlier, most of the emission factors for biogas production developed abroad are based on N, which is mostly ammoniacal nitrogen, making it difficult to compare with the emission factors calculated in this study.

However, in the case of the Netherlands, there is a case of applying wastes utilized for biogas production, which can be compared (Table 5). As a result of the comparison, the NH_3 emission factor in the Netherlands is 0.002 kgNH_3/ton-waste, which is somewhat lower than the 0.005 kgNH_3/ton-waste developed in this study, but it is within the maximum and minimum range calculated in this study, indicating that the values calculated in this study are similar.

Table 5. NH_3 emission factor based on the waste of the investigated biogas production facilities.

Classification	This study (kgNH_3/Ton-Waste)	Netherlands National Institute for Public Health and the Environment, Informative Inventory Report, 2020 [22] (kgNH_3/Ton-Waste)
NH_3 emission factor	0.005	0.002

3.2.2. NH_3 Emission Factors Based on Biogas Production at Biogas Production Facilities

The NH_3 emission factor based on the biogas production was determined and presented in Table 6. The results showed that the NH_3 emission factor from the biogas production facility was 0.150 kgNH_3/10^3 Nm^3-Biogas. The NH_3 emission factor for each biogas production facility was 0.023 kgNH_3/10^3 Nm^3-Biogas from biogas production facility A, 0.166 kgNH_3/10^3 Nm^3-Biogas from biogas production facility B, and 0.192 kgNH_3/10^3 Nm^3-Biogas from biogas production facility C. The emission factor was largest from biogas production facility C, followed by biogas production facility B and biogas production facility A. In the case of NH_3 emission factors based on biogas production, it was difficult to compare with values from other studies because there were no studies developed or studied with the same base.

Table 6. NH_3 emission factor based on biogas production of the investigated biogas production facilities.

Site	**Mean (kgNH_3/10^3 Nm^3-Biogas)**	**SD (kgNH_3/10^3 Nm^3-Biogas)**	**Sampling**
A biogas production facility	0.023	0.025	31
B biogas production facility	0.166	0.419	122
C biogas production facility	0.192	0.263	84
Total	0.150	0.334	237

3.3. Waste Sector Emission by Biogas NH_3 Emission Factor

In Korea, NH_3 emissions are measured in the waste sector only from other waste treatment such as wastewater treatment. However, this study recognized NH_3 emissions from biogas production facilities, emphasizing the importance of measuring these emissions in the future. As mentioned in the Section 2.3, describing the factors considered for the emission factor, it is difficult to manage NH_3 emissions because it is not based on nitrogen content as is the case in other countries. Waste treatment and biogas production are managed statistically, so the emission factor can be calculated.

In this study, the results of the improvement of the current domestic air pollutant inventory were applied to the waste sector to check the feasibility of improving the NH_3 inventory and applying NH_3 emission factors for biogas production facilities (Figure 3).

As a result of applying the NH_3 emission factor based on biogas production, 68 tons/year of NH_3 was found to be emitted. This is approximately three times higher than the existing waste sector NH_3 emissions of 22 tons/year. If the existing NH_3 emissions from the waste sector and the NH_3 emissions from waste based on the emission factor are combined, a total of about 90 tons/year of NH_3 would be emitted. Applying the waste based NH_3 emission factor calculated in this study results in approximately 144 tons of NH_3 emissions per year, which is approximately six times higher than the existing waste sector's annual NH_3 emissions of 22 tons. When combined with NH_3 emissions from the waste sector, the total is 166 tons per year, of which 144 tons are not considered when applying the NH_3 emission factor based on waste and 90 tons when applying the NH_3

emission factor based on biogas production. This again confirms the need to develop emission factors that reflect country-specific characteristics to increase the reliability of the inventory.

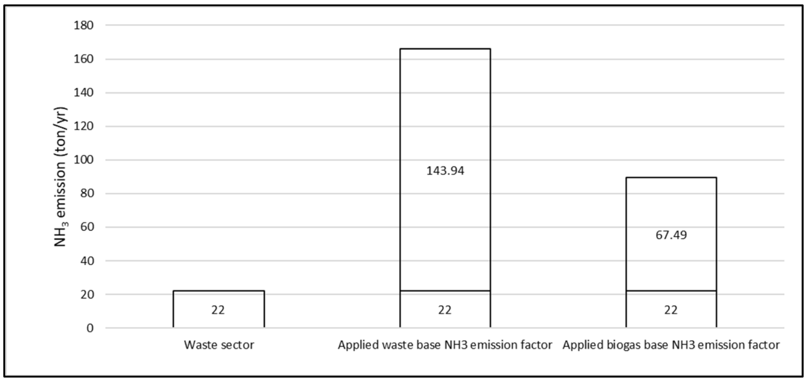

Figure 3. Changes in NH_3 emissions in the waste sector by the reflection of biogas production facilities.

The difference in the application of each unit is judged to be the difference between the amount of waste treated and the amount of biogas produced. The amount of waste processed is relatively high. In the actual field survey data, there were cases where biogas was not produced that day even if the waste was processed at the biogas production facility, so simple waste disposal statistics may not reflect this characteristic. Therefore, this study concludes that this difference is due to differences in the collection of related activity data.

3.4. Uncertainty of NH_3 Emission Factor at Biogas Production Facility

3.4.1. Uncertainty of NH_3 Emission Factors Based on Waste at Biogas Production Facilities

To assess the uncertainty of the NH_3 emission factor of the biogas production facility determined in this research, the Monte Carlo simulation was applied using "Crystal Ball", and the results are shown in Table 7.

Table 7. Uncertainty of the waste base, NH_3 emission factors at biogas production facility.

Site	Mean (kgNH_3/Ton-Waste)	95% Lower Confidence Level (kgNH_3/Ton-Waste)	95% Lower Confidence Level (kgNH_3/Ton-Waste)	Probability Density Function	Uncertainty Range
A biogas production facility	0.0012	0.0011	0.0014	Gamma distribution	−4.3~+3.7%
B biogas production facility	0.0035	0.0034	0.0037	Beta distribution	−2.9~+5.7%
C biogas production facility	0.0075	0.0070	0.0081	Lognormal distribution	−6.7–+8.0%

The PDF of the NH_3 emission factors for A biogas production facility based on the waste processing amount was analyzed as a Gamma distribution. The average was 0.0012 kgNH_3/ton-waste. The bottom 2.5% was 0.0011 kgNH_3/ton-waste at the 95% confidence level, and the top 97.5% was 0.0014 kgNH_3/ton-waste. The range of uncertainty of the NH_3 emission factor determined using these values was between −4.3 and +3.7% at the 95% confidence level.

The PDF of the NH_3 emission factor of B biogas production facility was analyzed as a Beta distribution. The average was 0.0035 kgNH_3/ton-waste. The bottom 2.5% at the 95% confidence level was 0.0034 kgNH3/ton-waste, and the top 97.5% was analyzed as 0.0037 kgNH_3/ton-waste. The uncertainty range of the NH_3 emission factor determined using these values was between −2.9 and +5.7% at the 95% confidence level.

The PDF of the NH_3 emission factor of C biogas production facility was analyzed as the Lognormal distribution. The average was analyzed to be 0.0075 kg NH_3/ton-waste. The bottom 2.5% was 0.0070 kgNH_3/ton-waste at the 95% confidence level, and the top 97.5% was 0.0081 kgNH_3/ton-waste. The uncertainty range of the NH_3 emission factor determined using these values was −6.7–+8.0% at the 95% confidence level.

3.4.2. Uncertainty of NH_3 Emission Factors Based on Biogas Production

The uncertainty of the NH_3 emission factors based on the biogas production is also presented in Table 8, where the Monte Carlo method was applied in the same manner as waste processing guidelines.

Table 8. Uncertainty of the biogas production base, NH_3 emission factors at biogas production facility.

Site	Mean (kgNH_3/10^3 Nm^3-Biogas)	95% Lower Confidence Level (kgNH_3/10^3 Nm^3-Biogas)	95% Lower Confidence Level (kgNH_3/10^3 Nm^3-Biogas)	Probability Density Function	Uncertainty Range
A biogas production facility	0.023	0.022	0.025	Gamma distribution	−8.3–+16.7%
B biogas production facility	0.168	0.154	0.182	Lognormal distribution	−8.3–+8.3%
C biogas production facility	0.194	0.179	0.211	Gamma distribution	−6.7–+8.0%

The PDF of the A biogas production facility NH_3 emission factor determined through this study based on the biogas production was analyzed as the Gamma distribution. The average was 0.023 kgNH_3/10^3 Nm^3-Biogas, and the bottom 2.5% at the 95% confidence level was 0.022 kgNH_3/10^3 Nm^3-Biogas, and the top 97.5% was 0.025 kgNH_3/10^3 Nm^3-Biogas. The range of uncertainty of the NH_3 emission factor determined by these values was between −8.3 and +16.7% at the 95% confidence level.

The PDF of the NH_3 emission factor of B biogas production facility was analyzed as the Lognormal distribution. The average was 0.168 kgNH_3/10^3 Nm^3-Biogas. The bottom 2.5% at the 95% confidence level was 0.154 kgNH_3/10^3 Nm^3-Biogas, and the top 97.5% was 0.182 kgNH_3/10^3 Nm^3-Biogas. The range of uncertainty of the NH_3 emission factor determined using these values was between −8.3–+8.3% at the 95% confidence level.

The PDF of the NH_3 emission factor of C biogas production facility was analyzed as the Gamma distribution. The average was 0.194 kgNH_3/10^3 Nm^3-Biogas. The bottom 2.5% at the 95% confidence level was 0.179 kgNH_3/10^3 Nm^3-Biogas, and the top 97.5% was 0.211 kgNH_3/10^3 Nm^3-Biogas. The uncertainty range of the NH_3 emission factor determined using these values was between −6.7 and +8.0% at the 95% confidence level.

3.4.3. Comparison of the NH_3 Emission Factors Uncertainty

The average emission factor of the total biogas production facilities was used to calculate the uncertainty, which was compared with the uncertainty of the emission factor employed overseas.

The PDF of the NH_3 emission factor based on waste processing was analyzed as the Lognormal distribution. The average was 0.0046 kgNH_3/ton-waste. The bottom 2.5% at the 95% confidence level was 0.0044 kgNH_3/ton-waste, and the top 97.5% was 0.0049 kgNH_3/ton-waste. The uncertainty range of the NH_3 emission factor determined using these values at the 95% confidence level was between −4.3 and +6.5% (Figure 4).

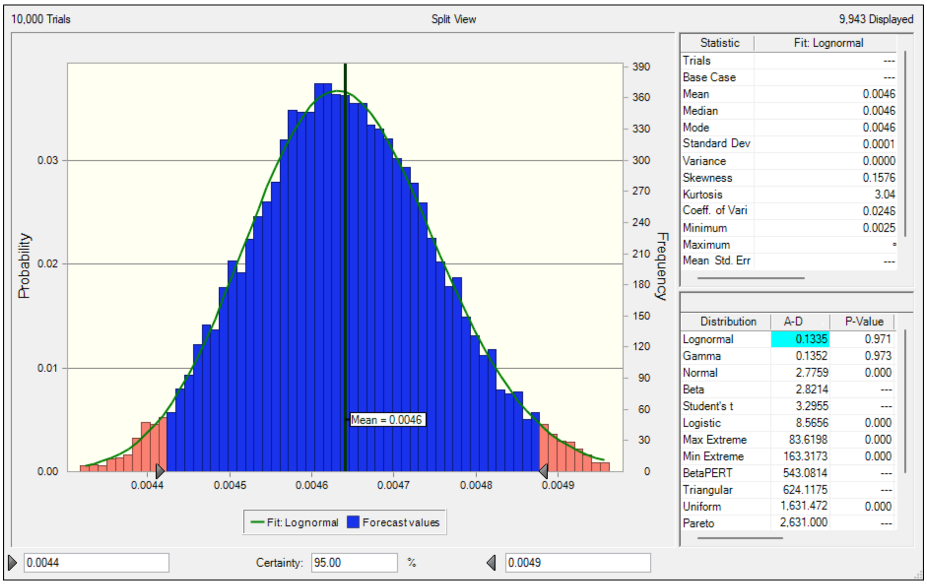

Figure 4. Uncertainty of the waste base NH_3 emission factor at biogas production facility.

The PDF of the NH_3 emission factor based on biogas production was analyzed as the Gamma distribution. The average was 0.1514 kgNH_3/10^3 Nm^3-Biogas. The bottom 2.5% at the 95% confidence level was 0.1428 kgNH_3/10^3 Nm^3-Biogas, and the top 97.5% was 0.1609 kgNH_3/10^3 Nm^3-Biogas. The uncertainty range of the NH_3 emission factor determined using these values at the 95% confidence level was between −5.7–+6.3% (Figure 5).

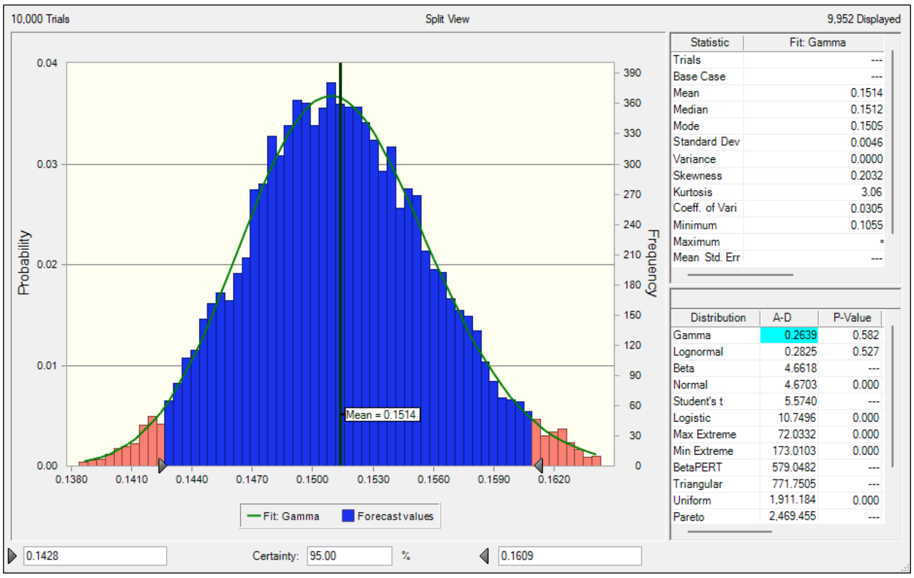

Figure 5. Uncertainty of the biogas production base NH_3 emission factor at biogas production facility.

In this study, NH_3 emission factors for biogas production facilities were not developed based on N, which is different from overseas, so it was difficult to compare the emission factors except for some studies.

However, it was possible to estimate the uncertainty because EMEP/EEA provides N-based emission factors with upper and lower limits with 95% confidence intervals. Therefore, to compare the level of uncertainty, the range of emission factors in EMEP/EEA was reestablished with uncertainty values and compared (Table 9). In addition, it was difficult to compare with other countries' values because the upper and lower limits of the 95% confidence interval are not presented in the case of other countries or the US EPA.

Table 9. Comparison NH_3 emission factors uncertainty at biogas production facility.

Classification			Uncertainty Range
This study	Waste base NH_3 emission factor at biogas production facility		−4.80%–+7.54%
	Biogas base NH_3 emission factor at biogas production facility		−5.04%–+6.50%
EMEP/EEA, 2019	5.B.1 Compost production	Compost production	−58.3%–+191.7%
		Windrow composting garden and park waste	−92.4%–+51.5%
	5.B.2 Biogas production	Biogas production	−40.7%–+82.2%
		Pre-storage	−44.4%–+66.7%
		Storage of non-separated digestate	−42.9%–+74.8%

A comparison with EMEP/EEA uncertainties shows that the uncertainty of the emission factors calculated in this study is much lower than the uncertainty of the 95% confidence intervals of the emission factors presented in EMEP/EEA.

According to the EMEP/EEA inventory guidebook, an emission factor with an uncertainty range of 10–30% falls under class A, indicating a high level of uncertainty. Therefore, the emission factors calculated in this study are categorized as high with low uncertainty.

South Korea uses the DARS proposed by the EPA in the United States to assess the uncertainty of air pollutants. The DARS method presents methods of scoring by reflecting the characteristics of the inventory. However, this method often relies on expert decisions and reflects subjective opinions. The EMEP/EEA air pollutant inventory guidebook recommends a quantitative presentation of the uncertainty and introduces a method of using uncertainty assessment in greenhouse gases [22]. In the IPCC guidelines related to greenhouse gas inventories, the Monte Carlo simulation is introduced as one of the uncertainty assessment methods and recommended to report certain air pollutants as indirect greenhouse gases [23]. Therefore, securing quantitative uncertainty data will be necessary to assess the emission factor of air pollutants as the same level of greenhouse gases in the future.

4. Conclusions

Ammonia (NH_3) emissions from South Korea's waste sector only account for the amount generated in wastewater treatment facilities. However, other countries also consider NH_3 emissions from the landfill of solid waste and biogas production. In this study, NH_3 emissions from biogas production facilities and the necessity of developing emission factors were reviewed. Additionally, base unit data and related content necessary for developing the NH_3 emission factor were reviewed for the biogas production facilities. The emission factors were estimated, and the uncertainty analysis was carried out.

Based on the findings of this study, the following points should be considered when developing NH_3 emission factors for biogas production facilities in Korea. Consideration of nitrogen-based unit when developing emission factors was found to be easier compared to overseas cases, but such statistical data is currently not available in Korea. The amount of waste processed can be identified statistically, but if two or more types of waste are processed together, the type and amount of waste must be continuously identified. Biogas production has the advantage that the unit load can be unified and activity data can be easily obtained. In this study, we developed and compared emission factors based on waste treatment and biogas production that are readily available in Korea.

A total of three biogas production facilities were studied, where NH_3 samples were extracted for analysis. Analysis showed that the total ammonia concentration range was between 0.04 and 7.99 ppm. The NH_3 emission factor was calculated based on a two-unit bases. The results showed that the emission factor based on waste were 0.005 kgNH_3/ton-waste and 0.150 kgNH_3/10^3 Nm^3-Biogas. Using the developed emission factors to calculate NH_3 emissions results in a total of 68 tons/year of NH_3 emissions based on biogas production and 144 tons/year based on waste. Given that NH_3 emissions from the waste sector in 2019 were 22 tons/year, emissions from biogas production facilities need to be considered, which requires the development of an emission factor.

The uncertainty of the emission factor was −4.80–+7.54% in the case of emission factor based on waste and −5.04–+6.50% in the case of emission factor based on biogas. The difference in uncertainty of the emission factor was not significant, but it was lower than the uncertainty of the overseas emission factor (maximum 191%, minimum −40.7%). Therefore, it would be better to develop and apply national emission factors.

Since the unit of analysis for developing emission factors for biogas production facilities is not much different between waste disposal and biogas production in terms of uncertainty, it is recommended to develop emission factors based on biogas production, considering the advantages of consistency of statistical data and administrative aspects.

The limitations of this study were determining the emission factors based on data from only three biogas production facilities, and a low variety of waste processing cases were identified. Moreover, the ultimate technologies that were used to treat air pollutants differ for each biogas facility. Meanwhile, this study is meaningful because it highlights the necessity of emission factor development by determining the NH_3 emission factors and applying the calculation of NH_3 emissions in the waste sector, which have not been previously determined and applied in South Korea. In addition, it is scientifically meaningful that the emission of NH_3 from biogas production facilities, units which should be considered in the development of emission factors, and emission factors that can be utilized in Korea, which have not been developed to date, are calculated and presented with uncertainties.

This study will lay the foundation for future work on the development of preliminary data for improving the reliability of South Korea's NH_3 inventory. In the future, if insufficient data previously presented as a limitation could be acquired, the NH_3 inventory of South Korea would be improved, and this will contribute to the management of fine particulate matter.

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