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Contribution of Skin-Derived Ammonia to Outdoor Atmospheric Ammonia Levels in Relation to Pedestrian Flow on a University Campus

Akihiro Hosomi and Yoshika Sekine *

Chemistry Course, Graduate School of Science, Tokai University, Hiratsuka 259-1292, Kanagawa, Japan
* Correspondence: yoshika@tokai.ac.jp

Abstract

Ammonia (NH_3) is a major atmospheric pollutant, and emissions from the human skin surface, although considered a minor source, may also contribute to atmospheric NH_3. However, the contribution of human-derived NH_3 to outdoor atmospheric NH_3 concentrations has not been well characterized under real-world environmental conditions. This study investigated the relationship between pedestrian flow and outdoor atmospheric NH_3 concentrations on a university campus. Two field experiments were conducted. In Experiment 1, atmospheric NH_3 was simultaneously collected at six sites during daytime and nighttime on class days and non-class days using passive samplers. On class days, NH_3 concentrations were significantly higher during the daytime than at nighttime at all six sites, whereas no significant day–night differences were observed on non-class days. In Experiment 2, NH_3 concentrations were measured for 1 h at 6.5 and 2.3 m above ground level, while the number of pedestrians was simultaneously recorded. A significant positive correlation was observed between NH_3 concentration and pedestrian flow at both 6.5 m ($r = 0.71$, $p < 0.001$) and 2.3 m ($r = 0.47$, $p = 0.028$). In contrast, CO_2 concentrations showed substantially smaller day-to-day variability and no significant correlation with pedestrian flow. Furthermore, a stronger correlation between NH_3 concentration and pedestrian flow was observed during the predominantly summer-clothing season ($r = 0.85$, $p < 0.001$) than during the predominantly winter-clothing season ($r = 0.61$, $p = 0.06$). These findings suggest that human-derived NH_3, particularly skin-derived NH_3, may contribute measurably to outdoor atmospheric NH_3 levels in environments with substantial pedestrian flow, and that this relationship may vary with clothing conditions. Further studies under different environmental and clothing conditions are needed to clarify the contribution of human-derived skin gases to outdoor air quality.

Keywords: ammonia; skin gas; human emission; outdoor air; pedestrian flow

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1. Introduction

Gaseous ammonia (NH_3) is the most abundant alkaline gas in the atmosphere and is a key nitrogen compound that has substantial effects on the nitrogen cycle in ecosystems, the secondary formation of atmospheric particulate matter ($PM_{2.5}$ and related particles), and climate change [1]. The Haber–Bosch process, developed by Fritz Haber and Carl Bosch in 1906, enabled a rapid increase in NH_3 production. The synthesized NH_3 has been used mainly as a fertilizer to promote crop growth and maximize agricultural yields [2,3], making agricultural fertilizer application one of the major sources of atmospheric NH_3

emissions. In addition to fertilizers, NH_3 is emitted from a wide variety of sources, including volatilization from animal waste, biomass burning, emissions from soils and agricultural crops, fossil fuel combustion, and emerging applications such as H_2 production, NH_3 fuel cells, and NH_3- internal combustion engines, as well as human excreta [1,4].

NH_3 emissions from human sweat were first suggested by Healy et al. in 1970 [5], who observed higher NH_3 levels in the indoor air of a room occupied by humans. It has also been reported that NH_3 emissions from human respiration are much lower than those from sweat [6]. Accordingly, NH_3 emissions from human sweat have been considered in global estimates of NH_3 emissions from various sources [7–9]. In recent years, the characteristics of trace gases released from human skin, collectively referred to as human skin gases, have become increasingly understood. NH_3 is recognized as a typical human skin gas that is directly released from the bloodstream through the skin, occasionally together with perspiration [10–12]. The estimated amounts of NH_3 produced in the human body and excreted through different routes are approximately 0.5 mol day^{-1} through urine (as urea), 0.0083 mol day^{-1} through the skin surface, and 0.00014 mol day^{-1} through respiration [11,13]. These estimates suggest that, except under episodic conditions such as the release of human faeces into the environment, skin-derived NH_3 may represent the largest contribution to human-derived NH_3 emissions.

Because NH_3 emissions from human skin are relatively small compared with those from other major sources, their contribution to the spatial and temporal variations in atmospheric NH_3 concentrations has rarely been discussed. However, Osada et al. [14] reported an interesting finding concerning temporal changes in atmospheric NH_3 concentrations in central Tokyo. In 2020, socioeconomic activities in Tokyo were severely restricted to prevent the spread of coronavirus disease (COVID-19), resulting in substantial changes in human mobility and automobile traffic. During this period, atmospheric NH_3 concentrations decreased markedly. Furthermore, air quality model simulations indicated that emissions from human bodies and automobile traffic contributed substantially to atmospheric NH_3 concentrations in central Tokyo. These findings suggest that, in densely populated areas where substantial pedestrian flows occur, NH_3 emissions from human skin may contribute to outdoor atmospheric NH_3 concentrations.

Reductions in urban atmospheric concentrations of nitrogen dioxide (NO_2), particulate matter 2.5 ($PM_{2.5}$), ozone (O_3), and volatile organic compounds (VOCs) have been reported in association with restrictions on human activities during the COVID-19 lockdowns [15–17]. However, in contrast to the study by Osada et al. [14], these studies did not discuss the potential contribution of human-derived chemical emissions associated with pedestrian flow to ambient air pollutant concentrations. Furthermore, field measurements investigating the influence of human presence on local outdoor atmospheric concentrations of chemical compounds remain extremely limited. Veres et al. [18] measured atmospheric VOCs at a soccer stadium to evaluate the localized contribution of human-derived VOCs, such as ethanol and acetone, in a densely populated environment. Romero-Barriuso et al. [19] proposed an occupancy and air quality model for outdoor mass events, using exhaled CO_2 as an indicator of air quality and ventilation conditions. However, these studies focused on atmospheric measurements in locations where large numbers of people gathered, rather than directly examining the relationship between pedestrian flow and atmospheric chemical concentrations. Moreover, NH_3 was not specifically investigated in these studies.

To the best of our knowledge, previous studies have provided only indirect circumstantial evidence regarding the potential contribution of human presence to atmospheric NH_3 concentrations, and no field study has directly examined the relationship between pedestrian flow and outdoor atmospheric NH_3 concentrations. Therefore, the objective of this study was to investigate the influence of pedestrian flow on outdoor atmospheric NH_3

concentrations through field measurements. Measurements were conducted on a university campus, where pedestrian flow varies substantially depending on the time of day. This study is the first field investigation to directly assess the contribution of pedestrian flow to outdoor atmospheric NH_3 concentrations under real-world conditions.

2. Methods

2.1. Field Study

The field study was carried out at the Shonan Campus of Tokai University, located in a suburban area of Hiratsuka City, Kanagawa Prefecture, approximately 60 km southwest of central Tokyo, Japan. The campus covers approximately 1 km^2 and accommodates approximately 23,000 students, faculty members, and staff, resulting in substantial pedestrian flow that varies depending on the time of day. It should be noted that this study was not intended to demonstrate the occurrence of ammonia-related air pollution on this campus or to identify its sources.

The field study consisted of two experiments. Experiment 1 aimed to compare outdoor NH_3 levels between daytime and nighttime and between class days and non-class days at six sampling sites using passive samplers (PS). Experiment 2 aimed to investigate the relationship between outdoor NH_3 levels and pedestrian flow at two sampling positions at different heights above the ground at a selected site using impinger-based sampling.

2.2. Experiment 1

Experiment 1 was conducted on 7 class days and 4 non-class days without rain or snow between October 2024 and July 2025. Atmospheric NH_3 was simultaneously collected at six sites, namely Buildings No. 6, 8, 16, and 18, the lawn, and the rooftop, as shown in Figure 1, using a double-face-type PS based on molecular diffusion according to Fick's law [20]. The PSs were deployed at heights of 2–6.5 m above the ground or on rooftops to avoid direct contact with pedestrians and exposure to exhaled breath plumes, as this study did not aim to assess personal NH_3 exposure in the breathing zone. The measurement period was divided into two consecutive 12-h periods. For each sampling day, the daytime period (08:00–20:00) was followed by the nighttime period (20:00–08:00), and the daytime and nighttime measurements were treated as a paired set for statistical analysis. This procedure was applied to both class days (weekdays with classes) and non-class days.

The collection principle and structure of the PS are described in detail in [20]. Briefly, the sampler consists of end caps, porous polyethylene membrane diffusers, and 13-mm-diameter trapping filters, all of which are assembled into a sampler body. The trapping filter was prepared by dipping a commercially available cellulose filter paper (Advantec, Tokyo, Japan, No. 1, 13 mm diameter) into a solution of 2% phosphoric acid and 1% glycerol in methanol, followed by drying in a vacuum desiccator. An example of the PS installation is shown in Figure 2. After sampling, the two trapping filters used on both sides of the sampler were transferred together into a glass vial. The ammonia collected on the filters was extracted as NH_4^+ by shaking the filters with 8 mL of ultrapure water ((Merck, Darmstadt, Germany, Milli-Q® Type-1 ultrapure water system) at 150 rpm for 15 min, followed by filtration through a Millex®-HP 13-mm filter (Merck, Germany). After subtracting the mean blank value from the sample readings, the extracted NH_4^+ was subsequently quantified by ion chromatography. The collected amount of NH_4^+, W (μg), was converted to the ambient air concentration, C_w (μg m^{-3}), using Equation (1);

$$C_w = \frac{{}^{W}/_{t}}{D \times {}^{A}/_{L}} \quad (1)$$

where t is the sampling duration (=12 h), D is the molecular diffusion coefficient of NH_3 in air (=0.083 m^2 h^{-1}), estimated using Fujita's semi-empirical equation, which is based on the molecular weights, critical temperatures, and critical pressures of the two gases [21]. The A is the cross-sectional area of the diffusion path (m^2), and L is the diffusion path length (m) [22–24]. The A/L ratio is a geometrical parameter determined by the porous structure of the diffuser and was experimentally determined to be 0.0163 m in our previous study [20]. Because the NH_4^+ was extracted from the two trapping filters combined, the collected amount was divided by two. The resulting amount was assumed to represent NH_3, and the ambient NH_3 concentration was calculated accordingly. The C_W was then converted to C_v (ppb) using the sampling temperature, T (K), and the molar mass of NH_3 (g mol^{-1}), as shown in Equation (2).

$$C_v = C_w \times \frac{22.4}{M} \times \frac{T}{273} \quad (2)$$

Because significant contamination of the trapping media was detected in the blanks, the limit of detection (LOD) was calculated as three times the standard deviation of the blank measurements. The LOD of the PS was 0.96 ppb at 298 K for a 12-h sampling period, calculated using Equations (1) and (2). This value indicates that the PS can potentially be used to measure NH_3 concentrations in suburban environments.



Figure 1. Sampling sites for the measurement of outdoor atmospheric NH_3 at the Shonan Campus of Tokai University, Kanagawa, Japan.

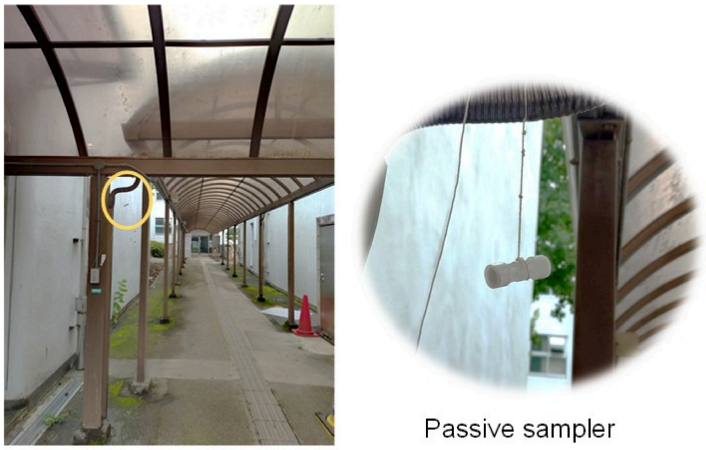


Figure 2. The passive sampler (PS) deployed at Building No. 6. The yellow circle indicates the locations where the PSs were deployed. The yellow circle indicates the locations where the PSs were deployed.

2.3. Experiment 2

Experiment 2 was conducted from July 2025 to May 2026 at a height of 6.5 m above ground level on the pedestrian bridge of Building No. 16, and additionally from September 2025 to May 2026 at 2.3 m above ground level along an outdoor walkway adjacent to Building No. 16. The sampling positions are shown in Figure 3. Sampling was conducted on 32 days at the 6.5-m height and 22 days at the 2.3-m height, without rain or snow, between 13:00 and 14:00. Simultaneously, the number of pedestrians was visually counted near each sampling position, and the outdoor carbon dioxide (CO_2) concentration was monitored using an Ondotori TR-76Ui (T&D Corporation, Matsumoto, Japan), which is equipped with a nondispersive infrared (NDIR) CO_2 sensor.

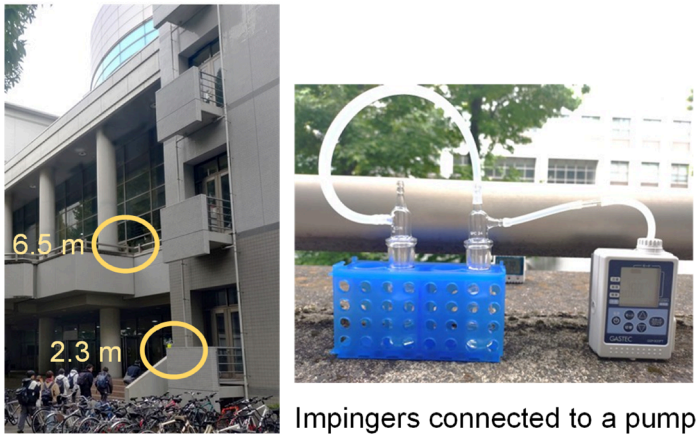


Figure 3. Sampling points for outdoor atmospheric NH_3 at Building No. 16 at heights of 2.3 and 6.5 m using serially connected impingers.

Atmospheric NH_3 was collected using two serially connected glass impingers (G-1 type, Sibata Scientific Technology, Tokyo, Japan), each containing 10 mL of ultrapure water, with a sampling pump (GSP-400FT, Gastec Corporation, Ayase, Japan) operated at a flow rate of 3.0 L h^{-1}. In a preliminary test using three serially connected impingers, no breakthrough of NH_3 was detected in the third impinger. Therefore, two impingers connected in series were used for the subsequent samplings. After sampling, the volume of the trapping solution

was adjusted to 10 mL with ultrapure water, and the collected NH_3 was determined as NH_4^+ by ion chromatography.

The summed amount of NH_4^+, W (μg), collected in the two impingers was converted to the ambient air concentration, C_W (μg m^{-3}), using the sampling volume (=3.0 L). The corresponding concentration in ppm, C_V, was also calculated using Equation (2). Because slight contamination of the trapping water was detected in the blanks, the limit of detection (LOD) was calculated as three times the standard deviation of the blank measurements. The LOD of the impinger method was 3.0 ppb at 298 K for a 1-h sampling period.

2.4. Determination of Ammonia by Ion Chromatography

The ion chromatography system consisted of an LC-20AD pump, a CDD-10Avp conductivity detector, a CTO-10Avp column oven, and an SIL-20A autosampler (all from Shimadzu Corporation, Kyoto, Japan), together with a system controller. The analytical conditions were as follows: column, Shodex IC YS-50 (4.6 mm i.d. × 125 mm; Resonac, Tokyo, Japan); eluent, a mixture of 3.0 mM aqueous phosphate solution and acetonitrile (90:10, *v*/*v*), under isocratic conditions; injection volume, 10 μL; and column oven temperature, 313 K. Calibration standards of ammonium ion were prepared in Milli-Q water(Merck, Darmstadt, Germany, Milli-Q® Type-1 ultrapure water system) at concentrations of 0.0, 0.20, 0.50, 2.0, and 5.0 mg L^{-1} using ammonium sulfate. The calibration curve showed a good linear relationship between ammonium concentration and peak area ($R^2 = 0.99$). Of the reagents, ammonium sulfate and acetonitrile were purchased from Kanto Chemical Co., Inc. (Tokyo, Japan). and phosphoric acid was purchased from FUJIFILM Wako Pure Chemical Corporation. (Tokyo, Japan).

2.5. Statistical Analysis

Statistical analyses were conducted using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA). Differences in outdoor atmospheric NH_3 concentrations between daytime and nighttime were analysed using the paired *t*-test. Pearson's correlation coefficients were calculated to assess the relationships between NH_3 or CO_2 concentrations and pedestrian flow. Unless otherwise indicated, statistical significance was set at $p < 0.05$.

3. Results

3.1. Comparison of NH_3 Levels Between Daytime and Nighttime (Experiment 1)

Figure 4 shows the outdoor atmospheric NH_3 concentrations measured at six sites on the university campus during the daytime (08:00–20:00) and nighttime (20:00–08:00) on class days and non-class days. The bars represent the mean of seven measurements for class days and four measurements for non-class days, and the error bars indicate the standard deviation.

On class days, NH_3 concentrations were significantly higher during the daytime than during the nighttime at all six sampling sites. Among the six sampling sites, the highest mean daytime NH_3 concentration was observed at Building No. 6, followed by Buildings No. 18, 16, and 8, whereas relatively low concentrations were observed in the lawn area and on the rooftop. The difference between the highest and lowest mean daytime NH_3 concentrations among the six sites was 3.0 ppb. In contrast, the difference between the highest and lowest mean nighttime NH_3 concentrations was only 1.8 ppb.

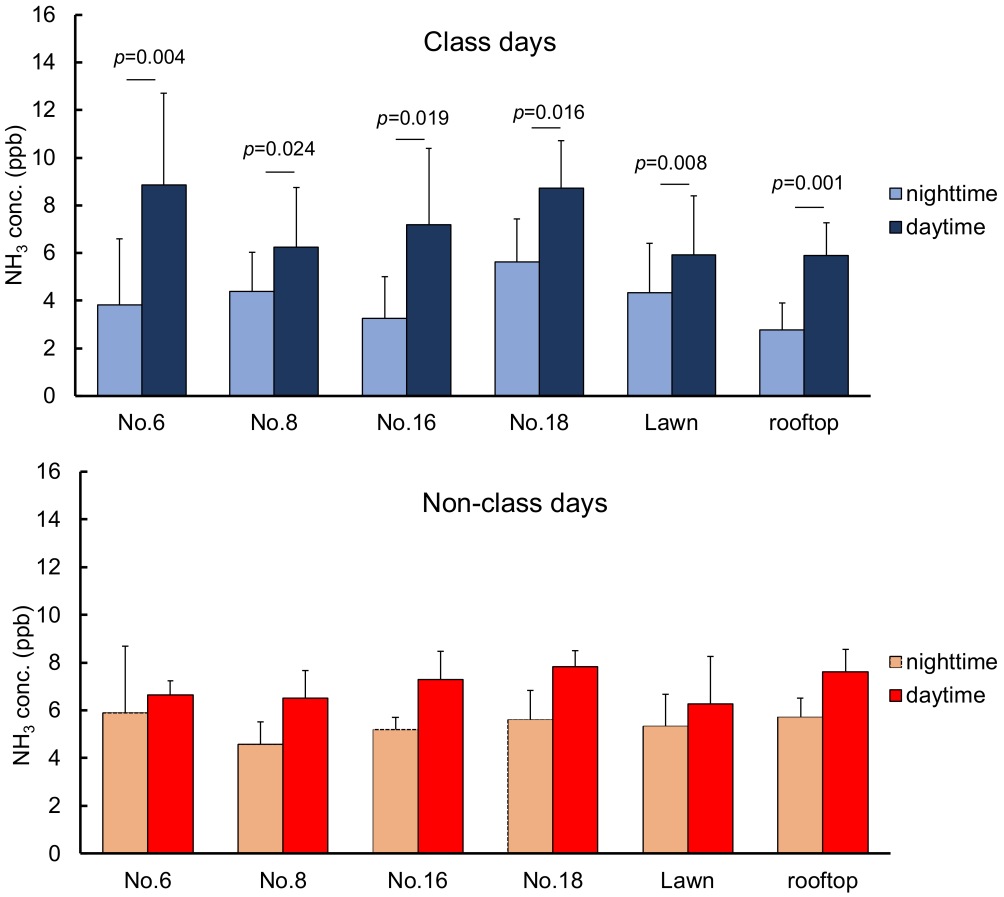


Figure 4. Comparison of outdoor atmospheric NH_3 concentrations between daytime and nighttime on class days (top, $n = 7$) and non-class days (bottom, $n = 4$).

The largest daytime–nighttime difference in NH_3 concentration was observed at Building No. 6, with an average difference of 5.0 ppb, followed by Building No. 16 (3.9 ppb), Building No. 8 (3.4 ppb), and Building No. 18 (3.1 ppb). The smallest difference was observed in the lawn area (1.0 ppb). Although the rooftop, which is normally restricted to authorized personnel, showed relatively low NH_3 concentrations compared with the other sampling sites, a clear daytime–nighttime difference was also observed, with an average difference of 3.1 ppb. Detailed results are provided in Table S1 in the Supplementary Material.

In contrast, no significant differences in NH_3 concentrations between daytime and nighttime were observed on non-class days. The differences among the six sampling sites were also relatively small, with differences between the highest and lowest mean NH_3 concentrations of 1.5 ppb during the daytime and 1.3 ppb during the nighttime.

The area surrounding the campus is primarily residential, although agricultural fields and small wooded areas are also present, and vehicular traffic occurs in the vicinity. These surrounding sources may contribute to the background level of outdoor atmospheric NH_3 on the campus. Nevertheless, differences in meteorological conditions and other factors between the measurement periods may have influenced the observed NH_3 concentrations. However, the contributions of other NH_3 sources are unlikely to increase directly with pedestrian flow on campus. In addition, the non-class days in this study included not only Sundays and national holidays but also weekdays without classes. Although daytime NH_3 concentrations on class days and non-class days should be compared with caution because the sampling was conducted on different days, concentrations tended to be higher on class days, when more students were present on campus. This finding suggests that pedestrian flow on campus may be one of the factors contributing to outdoor NH_3 concentrations.

3.2. Relationship Between NH_3 Concentrations and Pedestrian Flow (Experiment 2)

As shown in Figure 5, outdoor atmospheric NH_3 and CO_2 concentrations were plotted against the number of pedestrians during the period from 13:00 to 14:00 at two sampling positions: 6.5 m above ground level on the pedestrian bridge of Building No. 16 and 2.3 m above ground level along an outdoor walkway adjacent to Building No. 16.

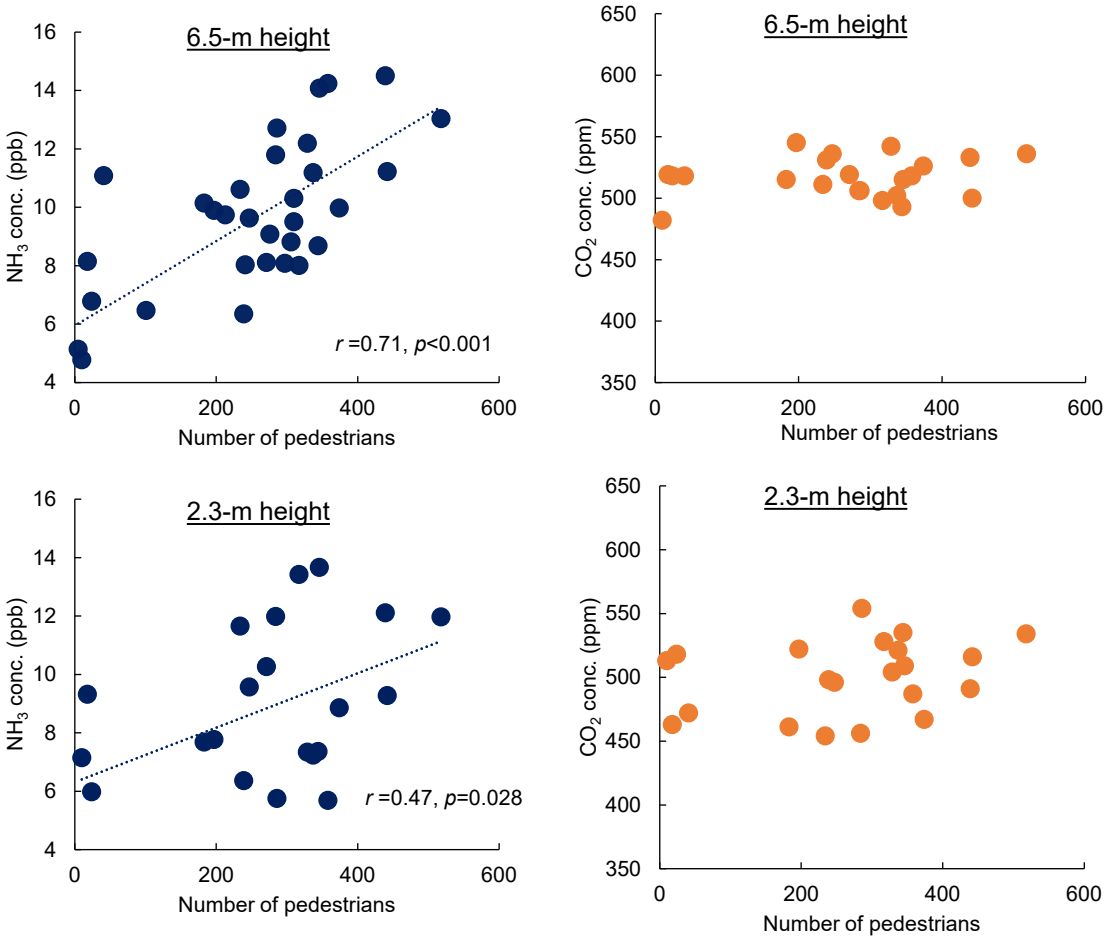


Figure 5. Scatter plots of outdoor atmospheric NH_3 and CO_2 concentrations (**left**) and (**right**), respectively) versus the number of pedestrians at Building No. 16 at heights of 2.3 m (**bottom**) and 6.5 m (**top**).

At 6.5 m above ground level, the NH_3 concentration ranged from 4.8 to 15 ppb, with a coefficient of variation (CV) of 28%. At 2.3 m, the NH_3 concentration ranged from 5.7 to 14 ppb, with a CV of 31%. A significant positive correlation was observed between NH_3 concentration and the number of pedestrians at both 6.5 m ($r = 0.71$, $p < 0.001$) and 2.3 m ($r = 0.47$, $p = 0.028$).

In contrast, atmospheric CO_2 concentrations showed substantially less variation among sampling days than NH_3 concentrations. At 6.5 m, CO_2 concentrations ranged from 482 to 545 ppm, with a CV of 3.1%, whereas at 2.3 m they ranged from 454 to 554 ppm, with a CV of 5.7%. No significant correlation was observed between CO_2 concentration and the number of pedestrians at either sampling position.

4. Discussion

Humans emit both NH_3 and CO_2. NH_3 is emitted from the skin surface [10,11], whereas CO_2 is primarily released through respiration [25,26]. However, their behaviours

differed markedly in the present study. NH_3 concentrations showed significant positive correlations with pedestrian flow at both sampling heights, whereas CO_2 concentrations showed no significant correlation. In addition, NH_3 concentrations showed substantially greater day-to-day variability than CO_2 concentrations, with CVs of 28% and 3.1% at 6.5 m above ground level, respectively.

These differences may be related to the relative contributions of human-derived emissions to their ambient concentrations. CO_2 is present in outdoor air at a relatively high background concentration, whereas NH_3 occurs at much lower concentrations. Therefore, variations in human-derived NH_3 emissions may be more readily reflected in ambient NH_3 concentrations than variations in human-derived CO_2 emissions. The significant positive correlations between NH_3 concentration and pedestrian flow observed in this study support the possibility that human-derived NH_3 contributes measurably to outdoor atmospheric NH_3 levels at this site. It should also be noted that the measurement period in Experiment 2 (13:00–14:00) included the lunchtime interval between classes, during which the use of cafeterias and public restrooms, which are potential sources of CO_2 and NH_3 emissions, was expected to increase with pedestrian flow. However, indoor air from these facilities is mechanically exhausted to the rooftops of the respective buildings. Therefore, their potential influence on outdoor concentrations was considered unlikely to have substantially affected the results shown in Figure 5. In addition, the increase in pedestrian flow within the campus was not expected to affect vehicle traffic on the roads adjacent to the campus, although vehicle exhaust can also be a source of NH_3 [27]. Smoking can also be a source of NH_3 [28,29]; however, smoking is prohibited by law on university campuses in Japan. Although no significant sex- or age-related differences in dermal NH_3 emission have been reported, dermal NH_3 emission can be affected by temperature. In addition, although the effect has not yet been fully clarified, clothing may affect the emission of skin-derived NH_3 from the body surface. Therefore, the NH_3 data obtained at the 6.5-m height were stratified into two periods according to predominantly worn clothing: a predominantly summer-clothing season (July–October) and a predominantly winter-clothing season (November–May). Scatter plots were then prepared for each period.

As shown in Figure 6, a strong correlation was observed during the predominantly summer-clothing season ($r = 0.85$, $p < 0.001$, $n = 22$). During the predominantly winter-clothing season, a positive association was also observed, although it did not reach statistical significance ($r = 0.61$, $p = 0.06$, $n = 10$). We also examined the relationships between NH_3 concentration and outdoor air temperature, relative humidity, and discomfort index during the measurements. However, none of these variables showed a clear pattern that supported a stratification comparable to that shown in Figure 6.

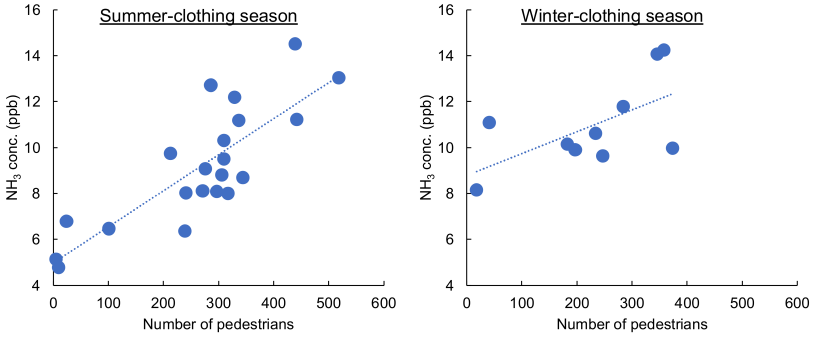


Figure 6. Scatter plots of outdoor atmospheric NH_3 concentration versus the number of pedestrians at Building No. 16 at a height of 6.5 m during the predominantly summer-clothing season (**left**) and predominantly winter-clothing season (**right**).

Furukawa et al. [11] reported a whole-body dermal NH_3 emission rate of 5.9 ± 3.2 mg h^{-1} $person^{-1}$ in healthy young subjects. However, this value was obtained under conditions in which the subjects were unclothed. Meanwhile, Li et al. [30] reported that adults and older adults wearing long clothing emitted approximately 0.4 mg h^{-1} $person^{-1}$ at 25 °C, increasing to 1.4 mg h^{-1} $person^{-1}$ at 29 °C in a controlled-chamber study. These findings suggest that the whole-body dermal NH_3 emission rate is influenced by the thermal environment and clothing selection. Clothing selection is influenced not only by the current thermal environment but also by seasonal effects and recent thermal history [31,32]. The present findings suggest that the relationship between pedestrian flow and outdoor atmospheric NH_3 concentrations may be associated with clothing conditions, potentially because clothing affects the emission of skin-derived NH_3.

Several limitations should be considered when interpreting the findings of this study, as atmospheric NH_3 concentrations and human-derived NH_3 emissions are influenced by multiple factors that were not fully accounted for in the present study. Outdoor atmospheric NH_3 concentrations are strongly influenced by topography and meteorological conditions, including temperature, precipitation, wind speed, and atmospheric mixing, as well as by surface characteristics that affect NH_3 deposition [33–35]. In addition, dermal NH_3 emission may be affected by various physical, physiological, and psychological conditions [10,11], as well as dietary intake [36] and illness [37]. The findings of the present study were obtained at a single location and during a specific period on a university campus where students were the predominant pedestrians. Therefore, the generalizability of these findings is limited. However, pedestrians may temporarily congregate in various outdoor environments, such as university campuses, transportation hubs, stadiums, festival venues, and commercial areas. In such settings, human-derived emissions may contribute to local outdoor pollutant concentration, highlighting the value of conducting field measurements at other types of locations in future studies. On the other hand, as pointed out by Osada et al. [13], in densely populated urban areas such as central Tokyo, human-derived NH_3 may potentially affect atmospheric NH_3 concentrations at the urban scale. Therefore, field measurements are needed to quantitatively assess the contribution of human presence to atmospheric NH_3 concentrations while accounting for local traffic composition and other potential emission sources in the surrounding areas that were not fully accounted for in the present study.

In addition to NH_3, numerous inorganic and organic compounds have been detected in human skin gas, and their potential contributions to outdoor air quality are also of interest. Further studies are needed to investigate the extent to which pedestrian flow affects outdoor atmospheric concentrations of various skin-derived gases under different environmental and clothing conditions.

5. Conclusions

This study investigated the relationship between pedestrian flow and outdoor atmospheric NH_3 concentrations on a university campus. In Experiment 1, NH_3 concentrations were significantly higher during the daytime than during the nighttime on class days at all six sampling sites, whereas no significant day–night differences were observed on non-class days. The larger daytime–nighttime differences observed at some sites with substantial pedestrian flow suggested a possible contribution of human-derived NH_3 to outdoor atmospheric NH_3 levels.

In Experiment 2, significant positive correlations were observed between outdoor NH_3 concentration and the number of pedestrians at both 6.5 m and 2.3 m above ground level. In contrast, outdoor CO_2 concentrations showed substantially smaller day-to-day variability and no significant correlation with pedestrian flow. These findings suggest that

human-derived NH_3, particularly skin-derived NH_3, may contribute measurably to outdoor atmospheric NH_3 levels in environments with substantial pedestrian flow.

Furthermore, the relationship between pedestrian flow and NH_3 concentration differed according to the predominantly worn clothing season. A strong correlation was observed during the predominantly summer-clothing season, whereas the correlation was weaker and did not reach statistical significance during the predominantly winter-clothing season. This finding suggests that clothing conditions may affect the contribution of skin-derived NH_3 to outdoor atmospheric NH_3 levels.

Overall, previous studies have provided only indirect circumstantial evidence for a contribution of human presence to atmospheric NH_3 concentrations, whereas the present study provides field-based evidence of a direct association between pedestrian flow and outdoor atmospheric NH_3 concentrations. These findings provide new insight into the potential contribution of human-derived NH_3 to outdoor air quality in environments with substantial pedestrian activity. Further studies under different environmental and clothing conditions and in different outdoor environments are needed to clarify the contribution of human-derived skin gases to outdoor air quality.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos17111137/s1, Table S1: Detailed daytime and nighttime NH_3 concentrations and the corresponding differences (Experiment 1).

Author Contributions: Conceptualization, A.H. and Y.S.; methodology, A.H. and Y.S.; validation, A.H. and Y.S.; formal analysis, A.H. and Y.S.; investigation, A.H. and Y.S.; data curation, A.H. and Y.S.; writing—original draft preparation, A.H. and Y.S.; writing—review and editing, A.H. and Y.S. All authors have read and agreed to the published version of the manuscript.

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