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RESEARCH

Time-weighted assessment of personal PM2.5 exposure of patients with allergies using portable monitors in Seoul Metropolitan Area, Korea

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Abstract Patients with allergies are more sensitive to fine particulate matter (PM2.5) than the general population; however, since PM2.5 exposure levels are influenced by microenvironments, time, and activity patterns, epidemiological studies using conventional stationary monitors face challenges in accurately estimating personal exposure levels. Therefore, this study analyzed the personal PM2.5 exposure characteristics of 86 individuals with allergies living in Seoul using portable monitors and GPS units from February to April 2024. The Kolmogorov–Smirnov test confirmed that the measured PM2.5 concentrations did not follow a normal distribution. Therefore, non-parametric statistical methods such as the Kruskal–Wallis and Wilcoxon rank-sum tests were used to assess statistically significant differences in PM2.5 concentrations. Over 90% of their time was spent indoors, with outdoor environments and schools (weekdays) and transportation (weekends) having the highest average PM2.5 concentrations. The lowest PM2.5 concentrations were consistently observed at home on both weekdays (12.76 μg/m^3) and weekends (13.46 μg/m^3). Despite this, the time spent at home resulted in the highest integrated exposure levels (weekdays: 58.25%; weekends: 71.14%). The highest levels of time spent and integrated exposure at home were similarly observed across all five subpopulations (child, student, employed, unemployed, and housewife). The average PM2.5 exposure concentrations did not exceed the WHO 24-h PM2.5 exposure guideline of 15 μg/m^3. However, analysis of the 5-min interval personal PM2.5 exposure concentrations revealed that participants exceeded this threshold 5.9% and 31.25% of the time on weekdays and weekends, respectively, indicating a higher frequency of high-concentration exposure on weekends. These findings quantitatively identify the primary microenvironments where patients with allergies are exposed to PM2.5 during the day and demonstrate that personalized air quality information provides better insights into personal PM2.5 exposure sources. These results should serve as foundational data for technology development aimed at elucidating the correlation between PM2.5 exposure and allergic diseases and for providing personalized air quality management guidelines.

Keywords Particulate matter · Allergic diseases · Personal exposure · Exposure assessment

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Introduction

Epidemiological studies have shown that particulate matter (PM) is associated with increased mortality and exacerbation of respiratory and cardiovascular diseases (Liu et al., 2019). Among these, fine particulate matter (PM2.5, particulate matter < 2.5 μm) has been classified as a human carcinogen by the International Agency for Research on Cancer (IARC Group 1). Due to its small particle size, PM2.5 can penetrate the terminal bronchioles and alveoli after passing through the airways when inhaled (Samara & Voutsa, 2005). Additionally, its large surface area per unit volume allows it to adsorb various hazardous chemicals such as heavy metals, volatile organic compounds, and formaldehyde (Hsiao et al., 2000; Mazziotti Tagliani et al., 2017), which may lead to severe adverse health effects.

Allergic diseases, characterized by abnormal immune hypersensitivity to specific allergens, have affected 20% of the population in developed countries over the past few centuries (Asher et al., 2004). PM can act as a trigger for antigen–antibody reactions to specific allergens within the body (He et al., 2016; Piao et al., 2021). Although the exact mechanisms underlying these interactions remain unclear (Wu et al., 2018), various studies have sought to elucidate the relationship between PM and allergic diseases. For instance, PM has been implicated in worsening airway inflammation and hypersensitivity in patients with asthma (Castañeda et al., 2017), increasing outpatient visits for conjunctivitis (Chang et al., 2012; Mimura et al., 2014), and contributing to the onset and severity of atopic dermatitis (Lai et al., 2023; Park et al., 2022).

Traditional epidemiological studies on PM exposure have relied on fixed monitoring station data to estimate population-wide exposure levels. However, such data have a low correlation with actual personal exposure levels (Avery et al., 2010). In particular, urban areas—characterized by high levels of urbanization and traffic—exhibit elevated PM levels compared to that in other regions (Duh et al., 2008), with urban heat island effects caused by high-rise buildings leading to air pollutant stagnation (Piracha & Chaudhary, 2022; Sarrat et al., 2006). Moreover, heating combustion in densely populated residential areas (Junninen et al., 2009) reduces the spatial and temporal resolution of monitoring station data, posing challenges for evaluating personal PM exposure in epidemiological studies.

Modern lifestyles, where individuals spend > 80–90% of their time indoors, have underscored the growing importance of indoor air quality research. Unlike outdoor environments, indoor spaces lack the diluting effects of wind, the sterilizing effects of ultraviolet light, and the washing effects of rain on air pollutants. Additionally, activities such as cleaning, cooking, and smoking act as notable indoor pollution sources. Therefore, in epidemiological studies, considering personal time-activity patterns and airborne pollutant concentrations in microenvironments (e.g., indoors, outdoors, and transportation) is crucial for accurately assessing personal exposure to air pollutants.

Various methods have been proposed to assess personal exposure. According to previous studies, personal exposure has been estimated by focusing on concentrations in specific microenvironments such as the home, school, and transportation (Faria et al., 2020; Karanasiou et al., 2014). However, even when occupying the same microenvironment, differences in exposure may occur depending on activity patterns or the specific location within the space (e.g., living room, bedroom, or bathroom at home) (Cepeda et al., 2017; Lung et al., 2021). A method of modeling indoor concentrations based on outdoor levels and meteorological variables has been used (Tang et al., 2018; Tong et al., 2020; Park et al., 2023), but according to these methodologies, limitations still remain due to restrictions to local conditions and the high variability between indoor and outdoor environments (Kearney et al., 2011; Kim et al., 2024a). The use of portable monitors or sensors carried by participants can significantly enhance the spatio-temporal resolution of data, contributing to a better understanding of personal PM2.5 exposure patterns (Clark et al., 2013; Morawska et al., 2018). Furthermore, integrating portable devices with GPS provides an opportunity to capture unintended or unreported time-activity patterns relevant to personal exposure (Steinle et al., 2015; Bo et al., 2017; Cunha-Lopes et al., 2019). This approach may be particularly important for vulnerable populations, such as individuals with allergic conditions (Lim et al., 2022).

This study aimed to overcome the limitations of existing epidemiological research, which has primarily estimated outdoor exposure levels to determine disease correlations. Specifically, we focused on evaluating personal PM2.5 exposure concentrations through a multi-faceted approach. First, real-time PM2.5 exposure concentrations were measured using low-cost, light-scattering-based devices. Second, the temporal distribution characteristics of personal PM2.5 exposure concentrations were analyzed using the collected data. Finally, based on time-activity diaries, PM2.5 exposure concentrations were calculated for various micro-environments (e.g., indoors, outdoors, and transportation) occupied by individuals. This approach—incorporating temporal and spatial variability—is expected to address the limitations of previous studies, enabling precise analysis of exposure–response relationships and improving the accuracy of health impact assessments.

Methods

This study involved 86 participants over a 2-month period, during which portable monitors were used to measure PM2.5 exposure levels, and location data were collected using a custom-designed GPS-based application. The collected PM2.5 exposure data were calibrated against reference instruments. Microenvironment exposure levels, occupancy rates, and time-weighted exposure were calculated using location data, followed by statistical analyses.

Study participants

This study is part of an effort to elucidate the association between allergic diseases (asthma, allergic rhinitis, conjunctivitis, and atopic dermatitis) and environmental exposure factors. The study subjects were selected from 86 outpatients, aged 1 to 66 years, who visited the Pediatrics and Otorhinolaryngology-Head and Neck Surgery Departments of Korea University Guro and Anam Hospitals for treatment of these allergic conditions. All participants resided in the Seoul metropolitan area (Fig. S1) and provided written consent to participate in the study (Table 1). The recruited participants were categorized into five subpopulations to identify exposure characteristics according to demographic groups. Based on the Korean Exposure Factors Handbook, individuals aged 0–6 years were classified as child, and those aged 7–19 years as student (National Institute of Environmental Research 2019a). The other participants were classified into employed, unemployed, and housewife groups, as they were presumed to have similar activity patterns (Lim et al., 2012; Chen et al., 2018; Kim et al., 2024b). This study was conducted with approval from the Institutional Review Board under the project titled "Development of Core Technologies for the Prevention and Management of Environmental Diseases" by the Korea Environmental Industry and Technology Institute (IRB No. 2022GR0384).

Personal PM2.5 exposure monitoring

From February 2024 to April 2024, PM2.5 concentrations were measured at 1-min intervals using a portable laser-scattering-based monitor (Picohome, Brilliant and Company Co., Ltd., Korea), certified as Grade 1 by the Ministry of Environment for fine-dust measurement devices. Researchers provided participants with training on how to use the portable monitors. Participants were instructed to carry the monitors at all times during the day and wear them near their breathing zone (Fig. 1). During the night, they were guided to place the monitors in close proximity to their breathing zone.

Recently, numerous studies utilizing low-cost air sensors (LCS), such as the portable monitor used in this study, have been conducted. However, LCS devices may yield varying results depending on operating conditions, such as relative humidity and temperature (Hua et al., 2021; Kim et al., 2010). To enhance the LCS reliability of the LCS used here, a correction factor was calculated using reference-grade equipment (GRIMM-11 A; GRIMM Aerosol Technik Ainring GmbH & Co. KG, Germany). The LCS measured values were corrected accordingly before use. Detailed information on the correction methods and correction factors employed here can be found in Park et al. (2024). The LCS and reference equipment specifications are summarized in Table S1.

Time-activity pattern investigation

To collect data on spaces occupied by study participants, we used a custom-designed application developed by our research team specifically for clinical purposes in this study (Waycen Inc, 2023). The custom-designed application, installed and used on smartphones, collects two types of data: first, passive

Table 1 Characteristics of study participants

Information		
Sampling period		2024.02.01–2024.04.01
Allergic diseases	Asthma	19
	Atopic dermatitis	33
	Conjunctivitis	7
	Rhinitis	27
Food allergy	Yes[a]	11
	No	75
Sex	Male	34
	Female	52
Smoke	Yes	3
	No	83
BMI[b]	Underweight	25
	Normal weight	28
	Pre-obesity	11
	Obesity class I	12
	Obesity class II	7
	Obesity class III	3
Description (mean ± S.D.)	Child	19 (2.95 ± 1.90)
	Student	14 (11.14 ± 2.14)
	Employed	38 (39.98 ± 11.38)
	Unemployed	7 (38.86 ± 11.35)
	Housewife	8 (43.93 ± 7.76)
Age in years (mean ± S.D.)	0–6	19 (2.95 ± 1.90)
	7–18	14 (11.14 ± 2.14)
	19–66	53 (39.30 ± 11.68)
	Total	86 (26.69 ± 18.71)

[a]Participants having been diagnosed in an outpatient clinic

[b]The BMI classification followed the Korean Obesity Classification Standard (Korea Disease Control and Prevention Agency. 2020)

data that are automatically collected, such as PM2.5 concentration data from a portable monitor and GPS coordinates (latitude and longitude) at 5-min intervals; second, active data that are manually entered by participants, such as time-activity diaries for identifying occupied spaces, as well as surveys for medication information and symptoms. The time-activity diaries were pre-categorized into six micro-environments: home, school, offices, other indoor areas, transportation, and outdoor. School includes all entrusted educational facilities such as private academies, daycare centers, and kindergartens, while other indoor areas include all indoor environments other than home, school, and office, such as hospitals, cafes, and restaurants.

GPS coordinates may not be collected in indoor environments (Kjærgaard et al., 2010; Wahab et al., 2022). This application used network-based positioning to store location information in situations where GPS coordinates were difficult to obtain, such as in indoor environments or densely built-up areas, and corrected or replaced the stored locations with actual GPS data when available to ensure accurate positioning. GPS coordinates were collected according to allergic disease groups, and during the study period, the GPS collection rates were 80.68%, 75.15%, 80.68%, and 82.43% for asthma, atopic dermatitis, conjunctivitis, and rhinitis, respectively. These GPS coordinates were used to improve the accuracy of microenvironmental data based on time-activity diaries (Houston et al., 2011; Mazaheri et al., 2019). For home, school, and office, the reported time-activity patterns were mapped in conjunction with GPS data, particularly with respect to arrival and departure times. When participants were in these locations, any variation in GPS coordinates was not interpreted as movement, but rather considered stationary within the same environment (Nethery et al., 2008, 2014).

Fig. 1 Appearance of the participant equipped with the portable monitor

However, the low temporal resolution of 30-min intervals remains a limitation of this study in regard to unconsidered microenvironments.

Statistical analysis

To investigate the characteristics of PM2.5 exposure in the various microenvironments of the study participants, descriptive statistical analyses were conducted to calculate the mean, standard deviation, median, and interquartile range. Prior to statistical analysis, periods during which PM2.5 concentration data were missing due to portable monitor malfunction or battery discharge, or GPS coordinates were not collected because the custom-designed application was turned off or the smartphone was powered off, were excluded from the data processing. The Kolmogorov–Smirnov test confirmed that the measured PM2.5 concentrations did not follow a normal distribution (Table S2). Non-parametric statistical tests, including Kruskal–Wallis and Wilcoxon rank-sum, were applied to assess differences in the measured PM2.5 concentrations. Additionally, post hoc analyses were conducted to identify the sources of statistically significant differences. The significance level for all statistical tests was set at 0.05.

The collected time-activity pattern data were used to calculate the amount of time each participant spent in each microenvironment. The proportion of time spent in each microenvironment was calculated as a daily average, based on the percentage of time participants spent in each environment per day (Jeong & Park, 2017; Koehler et al., 2019; Li et al., 2023).

To quantitatively assess personal PM2.5 exposure in microenvironments, time-weighted exposure (TWE) was calculated by combining the measured personal PM2.5 concentrations with the time spent in each occupied space. TWE represents the total amount of PM2.5 exposure experienced by an individual across all microenvironments during a day (Dėdelė et al., 2019; Devi et al., 2013; Liu et al., 2022). The equation used to calculate TWE is as follows:

$$Time - WeightedExposure = \left(\sum_{j=1}^{m} c_{ij} \times t_{ij} \right) / T$$

where, c_{ij} represents the average concentration of $PM_{2.5}$ ($\mu g/m^3$) to which individual i was exposed in the microenvironment j, t_{ij} represents the time spent by individual i in the microenvironment j, and T denotes the average monitoring duration per day (h/day).

Results and discussion

Time-activity pattern

An analysis of the weekday and weekend time-activity patterns of the 86 study participants (Table 2) revealed that they spent the most time at home on both weekdays (59.07%) and weekends (72.50%). Over 90% of their time was spent indoors on both weekdays (94.11%) and weekends (90.58%), underscoring the importance of indoor air quality management. Among the microenvironments, excluding regular weekday activities such as offices and schools, there were no significant differences between weekdays and weekends in time spent in other indoor spaces or transportation. The most notable change was observed in outdoor environments, where time spent outdoors increased by ~1.6 times on weekends compared to that on weekdays. Among the five subpopulations, child, student, and worker—who have regular weekday activities—spent 18.56%, 24.37%, and 28.23% of their time in school and office on weekdays, respectively. In contrast, the unemployed and housewife groups, who do not have regular weekday activities, showed similar time-activity patterns between weekdays and weekends. The five subpopulations also exhibited time-activity patterns in home and indoor environments similar to those of the overall study participants. On both weekdays and weekends, all subpopulations spent the most time at home (weekdays, 49.07–78.53%; weekends, 60.13–83.77%) and spent over 80% of their time indoors.

The results were compared with the time-activity patterns of major activity spaces for South Korean adults (National Institute of Environmental Research 2019b) with similar results observed for time spent at home (weekdays, 62.92%; weekends, 70.83%), while slightly higher values were found for indoor spaces overall (weekdays, 86.50%; weekends, 85.42%). These findings are consistent with the study by Buonanno et al. (2013), which reported that children residing in central Italy spent 92% of their time indoors. Similarly, the time spent in transportation and outdoor environments in this study aligns with the findings of Chau et al. (2002), who reported that individuals in Hong Kong spent 3–7% of their time in these environments. Notably, on both weekdays and weekends, the unemployed and housewives spent more time outdoors than other subpopulations. This

Table 2 Time-activity patterns (%) by microenvironment

Microenvironment		Weekdays						Weekend					
		Child	Student	Employed	Unemployed	Housewife	Total	Child	Student	Employed	Unemployed	Housewife	Total
Indoor	Home	68.42%	62.89%	49.07%	78.53%	61.35%	59.07%	83.77%	71.35%	68.50%	79.73%	60.13%	72.50%
	Office	0.00%	0.00%	28.23%	0.00%	0.00%	12.39%	0.00%	0.00%	5.11%	0.00%	0.00%	2.18%
	School	18.56%	24.37%	0.18%	0.79%	0.00%	8.31%	0.37%	1.09%	0.04%	0.61%	0.00%	0.34%
	Other indoor areas	6.26%	9.11%	6.51%	8.15%	17.96%	8.14%	6.42%	12.33%	9.23%	4.02%	17.88%	9.57%
	Transportation	2.71%	1.44%	10.25%	3.21%	6.40%	6.20%	3.77%	5.31%	7.77%	3.52%	6.45%	5.99%
Outdoor		4.05%	2.19%	5.76%	9.32%	14.29%	5.89%	5.67%	9.92%	9.35%	12.12%	15.54%	9.42%

finding is consistent with a study of 8072 Seoul residents in 2022, which reported that the unemployed spent 1.44 times more time outdoors compared to the employed (Kim et al., 2024b).

An analysis of daily time-activity patterns by the hour (Fig. 2) revealed that on weekdays, most participants spent > 40% of their time between 08:00 and 17:00 in offices or schools, indicating these were the primary environments occupied during this period. On weekends, there was an increase in time spent outdoors and in other indoor spaces between 15:00 and 16:00, while > 50% of time was spent at home during all other hours. Across all hours, participants spent > 80% of their time indoors on weekdays and over 60% indoors on weekends. These time-activity patterns influence the concentration of PM2.5 to which individuals are exposed in their occupied microenvironments. To calculate integrated exposure levels for PM2.5 in each microenvironment, daily time-activity patterns were combined with personal PM2.5 exposure concentrations.

Temporal variation of personal PM2.5 concentration

The 5-min interval personal PM2.5 exposure concentrations measured using portable monitors were analyzed separately for weekdays and weekends (Fig. 3). The results showed a statistically significant difference in PM2.5 exposure concentrations between weekdays and weekends (Wilcoxon rank-sum test, $p < 0.05$).

On weekdays, two peaks of high PM2.5 concentrations were observed. The first peak occurred between 07:00 and 08:00, likely due to commuting activities and increased movement of the participants (Rojas-Bracho et al., 2004). The second peak was observed between 17:00 and 18:00, similar to findings from Faria et al. (2020), who reported PM peaks between 17:00 and 19:00 in households in Lisbon, Portugal. This increase in PM levels is thought to be associated with evening activities such as cooking and cleaning, consistent with previous studies (Rappazzo et al., 2014; Xu et al., 2018).

On weekends, PM2.5 levels showed a sharp increase around 08:00, followed by a gradual decline after 18:00. Similar to weekdays, the lowest PM2.5 concentrations during the 24-h period were recorded at night (weekdays, 11.56 μg/m^3 at 23:50; weekends, 12.29 μg/m^3 at 00:05). Compared to weekdays, weekends exhibited higher PM2.5 concentrations and wider confidence intervals, indicating greater variability in exposure levels.

The average PM2.5 exposure concentrations among the study participants with allergic diseases did not exceed the WHO 24-h PM2.5 exposure guideline of 15 μg/m^3 (weekdays, 13.38 μg/m^3; weekends, 14.40 μg/m^3). However, an analysis of the 5-min interval personal PM2.5 exposure concentrations revealed that participants exceeded the 15 μg/m^3 threshold 5.9% of the time on weekdays and 31.25% on weekends. This indicates a higher frequency of high-concentration PM2.5 exposure on weekends,

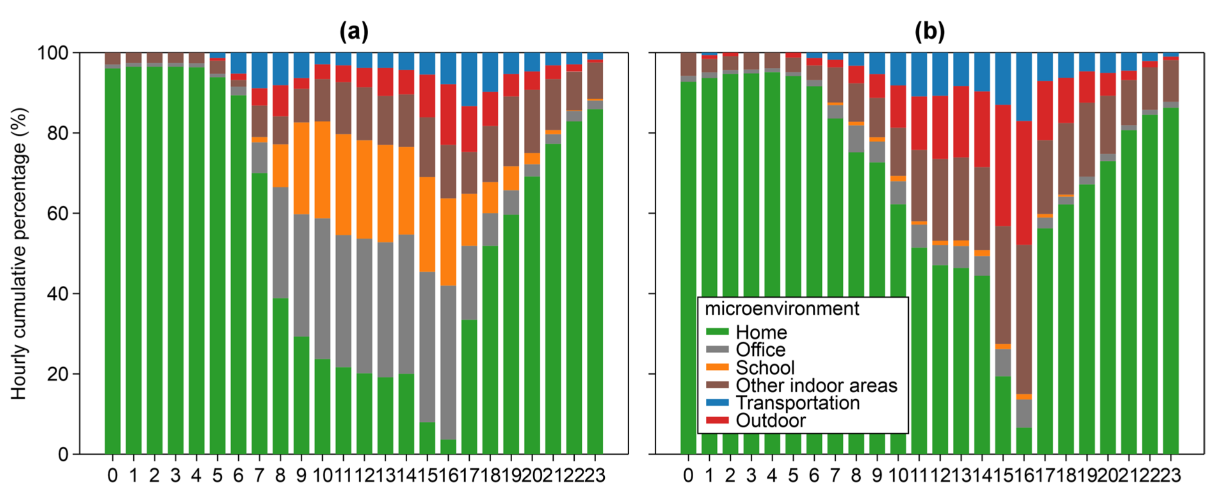

Fig. 2 Hourly cumulative time-activity pattern (%) by microenvironment during weekdays (**a**) and weekend (**b**)

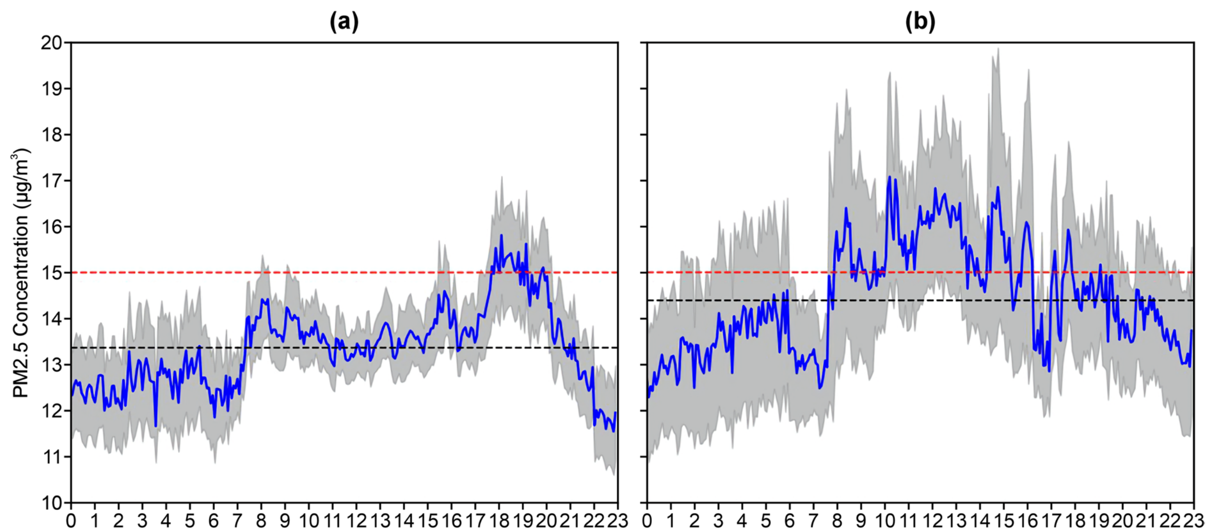

Fig. 3 Temporal variation of $PM_{2.5}$ concentration (μg/m^3) during weekdays (**a**) and weekend (**b**). The blue lines are the average concentration over all the participants. The shaded gray area represents 95% confidence intervals. The red dotted line is the WHO $PM_{2.5}$ 24-h guideline. The black dotted line is mean $PM_{2.5}$ concentration

likely due to increased indoor occupancy and heightened indoor activity levels.

This finding is particularly notable as individuals with allergic diseases are more sensitive to air pollutants compared to healthy individuals (Jang, 2014). Exposure to certain PM2.5 levels or short-term exposure to high PM2.5 concentrations can exacerbate allergic conditions (Annesi-Maesano et al., 2007; Li et al., 2022; Pénard-Morand et al., 2010; Pini et al., 2022). These results suggest the necessity of systematic evaluation and management of the health impacts on individuals with allergic diseases. Specifically, real-time assessment of personal exposure and analysis of spatiotemporal environmental factors contributing to high concentrations could inform the development of effective management strategies to mitigate health risks for this vulnerable section of the population.

PM2.5 concentration by microenvironment

The measured personal PM2.5 exposure concentrations were analyzed by the microenvironments occupied by the entire study participants (Table 3). Statistically significant differences in PM2.5 exposure concentrations were observed across all microenvironments (Kruskal–Wallis test, $p < 0.05$). To identify the sources of these differences, a post hoc analysis

Table 3 PM2.5 concentrations (μg/m^3) by microenvironment

		Weekdays				Weekend[a]				*p*-value
		N	Mean	S.D	Max	*N*	Mean	S.D	Max	
Indoor	Home	234,441	12.76	19.21	391.93	116,560	13.46	18.85	424.17	0.000[b]
	Office	64,342	12.87	11.03	286.89	5052	15.11	38.71	563.53	
	School	40,739	16.15	19.00	492.81	594	16.66	12.43	95.01	
	Other indoor areas	38,634	13.30	12.63	460.05	20,647	14.17	16.00	476.17	
	Transportation	17,699	14.13	18.70	464.21	7832	22.17	36.15	533.37	
Outdoor		17,870	16.48	15.05	418.65	12,052	18.35	17.01	404.57	

[a]Weekends are significantly different from weekdays (Wilcoxon rank-sum test, $p < 0.05$)

[b]Statistically significant differences among microenvironments (Kruskal–Wallis test, $p < 0.05$)

using Dunn's multiple comparison test was conducted (Table S3).

On weekdays, the highest PM2.5 concentrations were observed in outdoor environments (16.48 ± 15.05 μg/m^3) and schools (16.15 ± 19.00 μg/m^3), while the lowest concentration was found at home (12.76 ± 19.21 μg/m^3). PM2.5 concentrations measured in these microenvironments were statistically significantly different from those in other microenvironments ($p < 0.05$). Transportation, other indoor areas, and offices showed similar levels of exposure (14.13 ± 18.70 μg/m^3, 13.30 ± 12.63 μg/m^3, and 12.87 ± 11.03 μg/m^3, respectively), with no statistically significant differences observed between these pairs (transportation and other indoor areas, $p > 0.05$; transportation and office, $p > 0.05$).

On weekends, transportation exhibited the highest PM2.5 concentration (22.17 ± 36.15 μg/m^3) with a broader distribution compared to other microenvironments (Fig. S2). Transportation is a notable contributor to high PM2.5 concentrations due to the confined nature of the space, which limits pollutant dispersion (Goel & Kumar, 2015; Patton et al., 2016). Thus, the elevated weekend average PM2.5 concentrations for individuals with allergic diseases (Fig. 3) can be attributed to the increased time spent in transportation environments compared to weekdays (Fig. 2). Similar to weekdays, the lowest PM2.5 concentration on weekends was observed at home (13.46 ± 18.85 μg/m^3).

Personal PM2.5 exposure concentrations were also analyzed for five subpopulations (Table S4). Statistically significant differences in PM2.5 exposure concentrations were observed across all subpopulations (Kruskal–Wallis test, $p < 0.05$). On weekdays, among the microenvironments occupied by each subpopulation, students exhibited the highest exposure concentrations in transportation and school environments (26.94 ± 39.04 μg/m^3 and 20.28 ± 23.98 μg/m^3, respectively). The highest outdoor PM2.5 exposure concentrations during weekdays were attributed to the fact that all subpopulations, except students, showed the highest concentrations in the outdoor environment. On weekends, students also showed the highest exposure concentration in transportation (54.63 ± 63.38 μg/m^3) among all microenvironments, which likely contributed to the elevated PM2.5 concentrations observed in transportation for the entire study population (Table 3).

Time-weighted PM2.5 exposure by microenvironment

Using the personal PM2.5 exposure concentrations and time spent in occupied spaces, the integrated exposure levels for each microenvironment were calculated (Fig. 4a, b). On weekdays, 92.99% of the total integrated exposure occurred in indoor environments, compared to 89.43% on weekends, which is lower than weekdays. This contrasts with findings by Yang et al. (2019), who reported higher indoor personal integrated exposure on weekends (90%) compared to weekdays (85%).

Among all the microenvironments, the home accounted for the highest integrated exposure on both weekdays (58.25%) and weekends (71.14%), despite having the lowest average PM2.5 concentrations (weekdays, 12.76 μg/m^3; weekends, 13.46 μg/m^3). This pattern was consistently observed across the five subpopulations (Fig. 4c–h). All groups exhibited integrated exposures at home ranging from 53.27 to 75.46%, with the unemployed and child groups showing the highest home-based integrated exposures at 75.46% and 73.86%, respectively. This can be attributed to the marked amount of time spent at home. Homes often contain strong PM2.5 emission sources such as smoking, cooking, and heating (Ferro et al., 2004), and resident activities and household behavior can increase particle generation and resuspension (Adamkiewicz et al., 2011; Baxter et al., 2007). Cooking activities, depending on the type, can generate PM2.5 concentrations as high as 745 μg/m^3 (He et al., 2004), with peaks lasting up to 30 min (Qi et al., 2019). Additionally, burning incense at home has been identified as a considerable source of high indoor PM2.5 concentrations (Bootdee et al., 2016; Lee & Wang, 2004).

Although most of the PM2.5 exposure of the participants did not exceed the WHO 24-h average PM2.5 guideline of 15 μg/m^3 for most of the day, patients with allergies can experience adverse health effects even at low PM2.5 concentrations. Yorifuji et al., (2016a, 2016b) demonstrated that some population groups might face critical health risks at PM2.5 levels below the national guideline. Unlike other indoor microenvironments, such as hospitals, terminals, and gyms, homes are not subject to Korea's "Indoor Air Quality Management Act," highlighting the need for individual efforts to reduce PM2.5 levels

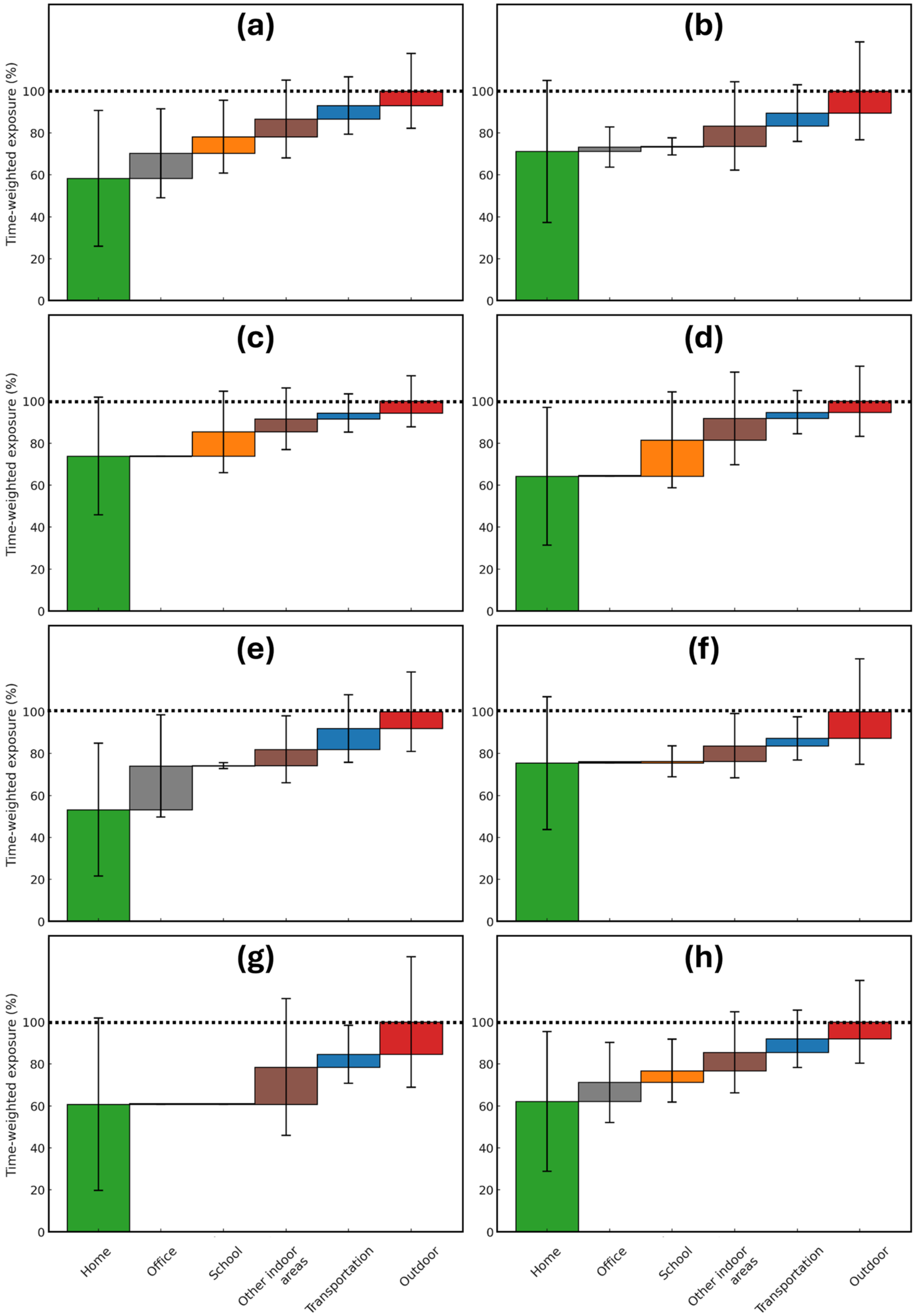

Fig. 4 Cumulative plots of time-weighted exposure (%) by microenvironment during each period: weekdays (**a**) and weekend (**b**), and across different subpopulations: child (**c**), student (**d**), employed (**e**), unemployed (**f**), housewife (**g**), and total (**h**). The error bar represents standard deviation

through measures such as ventilation and air purifier use. Thus, this study emphasizes the necessity of developing tailored guidelines for improving and maintaining indoor air quality in homes, specifically for individuals with allergic diseases. The participants in this study were patients with allergic diseases, and our research approach—based on a portable monitor, time-activity diaries, and GPS—enables real-time monitoring of these patients. It can help minimize exposure to PM2.5 by recording and predicting the time and location where high concentrations of PM2.5 occur.

This study has the following limitations. The number of participants (86) and the number of individuals in each of the five subpopulations (7–38) are insufficient to represent the overall population of Seoul residents or each corresponding subgroup. In addition, the study did not account for demographic and socioeconomic characteristics such as income, housing type and size, and household size. Personal characteristics such as the use of air purifiers, exposure to secondhand smoke, and ventilation rate were also not obtained. Nevertheless, given that most modern individuals spend considerable amounts of time in indoor environments, including the home, and utilize similar public transportation systems, the PM2.5 exposure trends presented here are likely representative. A further limitation is that this study qualitatively categorized the time-activity patterns of participants and focused solely on comparing exposure across simple micro-environments, without classifying personal activities such as cooking, cleaning, or incense burning. Therefore, future advanced studies should consider incorporating the time-activity patterns of participants in a more comprehensive manner and recruiting a greater number of participants to improve population representativeness.

Conclusion

The individuals with allergic diseases participating in this study were found to spend the majority of their time indoors, particularly at home, underscoring the need for effective indoor air quality management, including within homes. On weekdays, the highest average PM2.5 concentrations were observed in outdoor environments and schools, while on weekends, transportation showed the highest concentrations. Conversely, the lowest PM2.5 concentrations were consistently recorded at home on both weekdays and weekends. The highest time-weighted exposure levels were also observed at home on both weekdays and weekends and across all subpopulations, which are attributed to the considerable amounts of time spent in this environment. Although the average PM2.5 exposure concentrations for patients with allergic diseases did not exceed the WHO 24-h PM2.5 exposure guideline of 15 μg/m^3, the analysis of 5-min interval exposure concentrations revealed that participants exceeded the 15 μg/m^3 threshold during 5.9 and 31.25% of the time on weekdays and weekends, respectively. This study quantitatively identified the primary microenvironments where patients with allergic diseases are exposed to PM2.5 during the day. This study contributes to improving the health of patients with allergies and provides a foundational study for the development of personalized air quality management strategies.

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Author contribution Hyeok Jang: Conceptualization, Writing – original draft, Methodology, Investigation, Visualization, Resources Shin-Young Park: Data curation, Formal analysis, Software, Writing – review & editing Cheol-Min Lee: Project administration, Supervision, Funding acquisition, Validation.

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Data availability The datasets generated and/or analysed during the current study are not publicly available as the dataset contains personal information of our study participants (e.g., location data), but are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethical approval This study was conducted with approval from the Institutional Review Board under the project titled "Development of Core Technologies for the Prevention and Management of Environmental Diseases" by the Korea Environmental Industry and Technology Institute (IRB No. 2022GR0384).

Informed consent All participants provided written consent to participate in the study.

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