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Indoor and Outdoor Concentrations of Particulate Matter in an Airport Terminal Building: A Pilot Study at Soekarno-Hatta International Airport in Indonesia

Amy Kim * , **Lysandra Medal** , **Shuoqi Wang** and **Timothy Larson**

Department of Civil and Environmental Engineering, University of Washington, Campus Box 352700, Seattle, WA 98195, USA; medal@uw.edu (L.M.); shuoqw@uw.edu (S.W.); tlarson@uw.edu (T.L.)

* Correspondence: amyakim@uw.edu; Tel.: +1-206-685-0228

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Abstract: The air quality inside airport terminal buildings is a lesser studied area compared to ambient air quality at the airport. The contribution of outdoor particulate matter (PM), aircraft traffic, and passenger traffic to indoor PM concentration is not well understood. Using the largest airport in Southeast Asia as the study site (extends 17.9 square kilometers), the objective of this paper is to conduct a preliminary analysis to examine the mass concentrations of fine particles, including PM_1 and $PM_{2.5}$, and coarse particles $PM_{2.5-10}$ inside a four-story terminal building spanning 400,000 square meters in Jakarta, Indonesia. The results showed the indoor/outdoor (I/O) ratio of 0.42 for PM_1 with 15-min time lag and 0.33 for $PM_{2.5}$ with 30-min time lag. The aircraft traffic appeared to have a significant impact on indoor PM_1 and $PM_{2.5}$, whereas the passenger traffic showed an influence on indoor $PM_{2.5-10}$.

1. Introduction

The modern airport is a complex system with various types of facilities. Some components of the airport include air traffic control facilities, airfield including approach zones, a terminal complex, a utility communications network, supporting and service facilities, and ground access system [1]. Among them, the terminal buildings are unique in that they usually operate on a 24-h basis throughout the year and directly interact with majority of the passengers and airport employees.

In recent years, the importance of air quality assessment at the airport has gradually been acknowledged. A number of studies on air quality have been conducted in various facilities at airports around the world. Typical air quality parameters include total volatile organic compounds (TVOC), ultrafine particles (UFP) (particle diameters are less than 0.1 μm), fine particles (FP) or $PM_{2.5}$ (particle diameters are less than 2.5 μm), and PM_{10} (particle diameters are less than 10 μm). For example, the TVOC and other gas pollutants were evaluated inside the control tower by Helmis et al. [2], Mokalled et al. [3], and Tsakas and Siskos [4]. Helmis et al. [2] also measured the indoor $PM_{2.5}$ and PM_{10} mass concentration in the control tower [2]. Lee et al. [5] and Kungskulniti et al. [6] used $PM_{2.5}$ as a parameter to assess indoor air quality in airport smoking rooms. More studies can be found on ambient air quality at or near the airport. Hsu et al. [7,8] monitored the UFP level near runways at two U.S. airports to evaluate the impact of aircraft emissions on ambient air quality. Stacey [9] provided a most recent review of UFP related studies conducted at or near the airport with a focus on aircraft emission. Other studies have looked at particle size distributions in the ambient air near the airports, such as in Hudda et al. [10], Masiol et al. [11,12], and Fanning et al. [13]. However, indoor air quality

studies inside the airport terminal buildings are still limited for good reasons. Access to terminals and gates typically requires a thorough security check. Only passengers with boarding passes can wait by the entrance. Researchers with single-use escort passes still need to be accompanied by the airport security personnel to obtain measurements. Furthermore, obtaining the pre-approval from regulatory agencies adds another layer of complexity during the preparation phase of gaining permission to access the study site. These hurdles often act as discouragement for researchers during site selection of indoor air quality studies.

The airport terminal buildings experience a high fluctuation in the number of passengers that move through various parts of the building as well as the auxiliary spaces. Studies have shown that human activities, such as walking, often lead to particle resuspension which is an important indoor source of particulate matter [14,15]. Aircraft also generate a significant amount of particulate matter [16] as they idle near the ramps, taxi off the runway, and land onto the taxiways, which could infiltrate the building envelope and affect the air quality inside the terminal. Previous studies of airport workers have shown some evidence of correlation between chronic adverse respiratory symptoms and exposure to aviation fuel or jet stream exhaust [17,18]. Møller et al. [19] measured the exposure to UFP for five occupational groups at the airport. Workers who resided in the terminal buildings were considered a low exposure group or control group in these studies compared to other workers whose activities were outdoor or in closer proximity to aircraft. However, passengers spend most of their time at the airport inside the terminal buildings. It is equally important to understand the air quality inside the terminal building as opposed to other parts of the airport. Two recent studies by Zanni et al. [20] and Ren et al. [21] have examined the FP concentrations in airport terminal buildings in Italy and China, respectively. Other air quality parameters measured in the studies include TVOC [20] and UFP [21]. Whereas Zanni et al. concluded that the building's ventilation system appeared to be efficient in terms of filtration [20], Ren et al. demonstrated that the building failed to provide sufficient protection for passengers from $PM_{2.5}$ and UFP exposures [21]. Yet, neither study included the coarse particles $PM_{2.5-10}$ in the assessment. Brunekreef and Forsberg [22] have discussed the epidemiological evidence for effects of coarse particles on health and emphasized the importance of studying and regulating coarse particles separately from fine particles. A recent study by Deng et al. [23] found that coarse particles generated by crustal sources might have adverse health effects as strong as those of fine particles generated from combustion sources.

The objective of this paper was to conduct a pilot study with limited data to examine the mass concentrations of fine particles including PM_1 and $PM_{2.5}$, and coarse particles $PM_{2.5-10}$ inside Terminal 3 of the Soekarno-Hatta International Airport (SHIA) in Jakarta. The feasibility of estimating particle infiltration using time-lagged regression was evaluated. In addition, the effect of aircraft and passenger traffic on the concentration of fine and coarse particles was investigated.

2. Materials and Methods

2.1. Study Site

SHIA is Indonesia's most prominent international airport that serves the greater Jakarta area. This airport is in Benda, Tangerang, 20 km northwest of Central Jakarta. SHIA is the largest airport in Southeast Asia, the most active in the southern hemisphere [24], and the seventh most connected airport in the world, functioning as a "mega hub" [25]. This airport handled more than 63 million passengers in 2017. The airport extends 17.9 square kilometers with three main terminal buildings. Terminal 1, 2, and 3 were opened in 1985, 1991, and 2016 respectively. Terminal 3 (T3) was selected as the study site. It is a four-story building with 3290 full-time employees and 456 part-time employees. Figure 1 shows the sampling location where the objective air quality measurements were obtained.
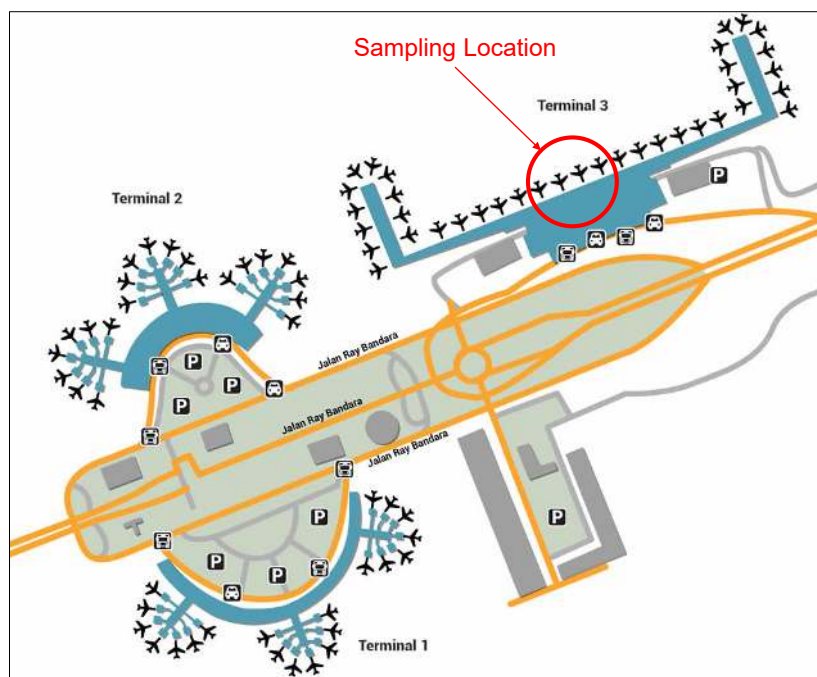
Figure 1. Location of field measurement in the center of Terminal 3 (Image source: https://www.airportshuttles.com/cgk-airport-terminals.php).

This study required an extensive approval process involving five different airport authorities. The approval prior to the research team's arrival was handled by the Airport Management Center. It included online and physical submission of the research proposal and follow-up communications with the Human Resources and General Affairs Department to obtain the official approval letter to conduct air quality measurement from 31 January to 20 February 2019. Upon arrival, a formal meeting was conducted with the officer in charge (OIC) team and the airport mechanical engineers who were responsible for the operation and maintenance of the Terminal 3 building. This was a critical meeting where the airport operation team provided a secondary site-specific approval for the data collection. The research team discussed the objectives of the study which facilitated the identification of the optimal locations for indoor and outdoor air quality measurements. The daily access to the study site included passing multiple security checkpoints and areas beyond the checkpoints required escort of at least two OIC employees. An access flow chart is shown in Figure 2.

2.2. Data Collection

2.2.1. Primary Data

Two units of the Particles Plus 7302-AQM Air Quality Monitor [26] were used to measure the indoor and outdoor particle mass concentrations. The monitor used long-life laser diode technology to detect particles in the range of 0.3–25 μm and was calibrated by the manufacturer. The two monitors were programmed to count the particles in a two-minute air sample at a flow rate of 2.83 liters per minute every five minutes.

The indoor and outdoor PM concentrations were measured at two sampling locations in this study, as shown in Figure 3. The indoor location was near one of the return air grilles in the boarding area. To keep the monitor in a secure location and from outdoor elements, the outdoor air was sampled through 10 feet of Bev-A-Line XX® [27] tubing which had a smooth inner lining that was appropriate for high-purity air sampling applications.
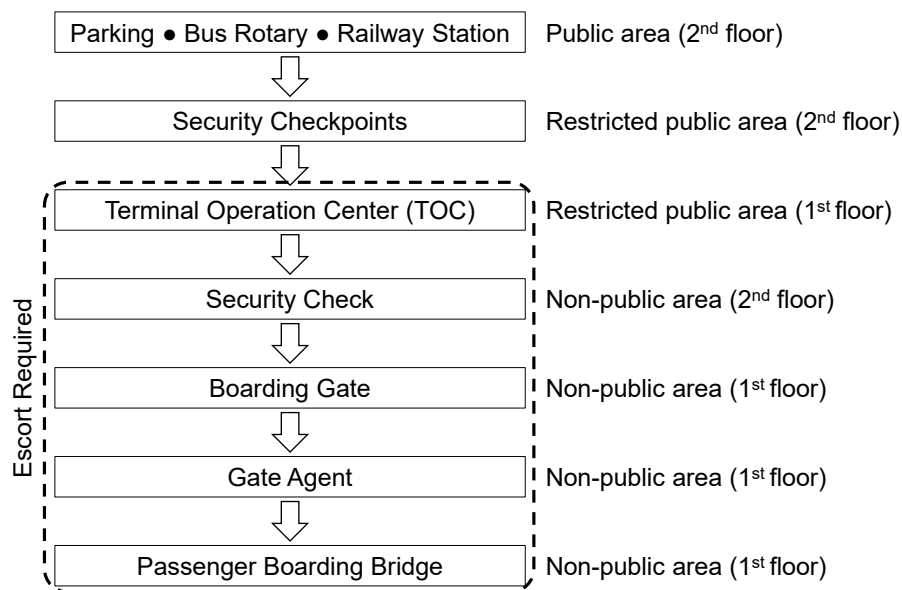
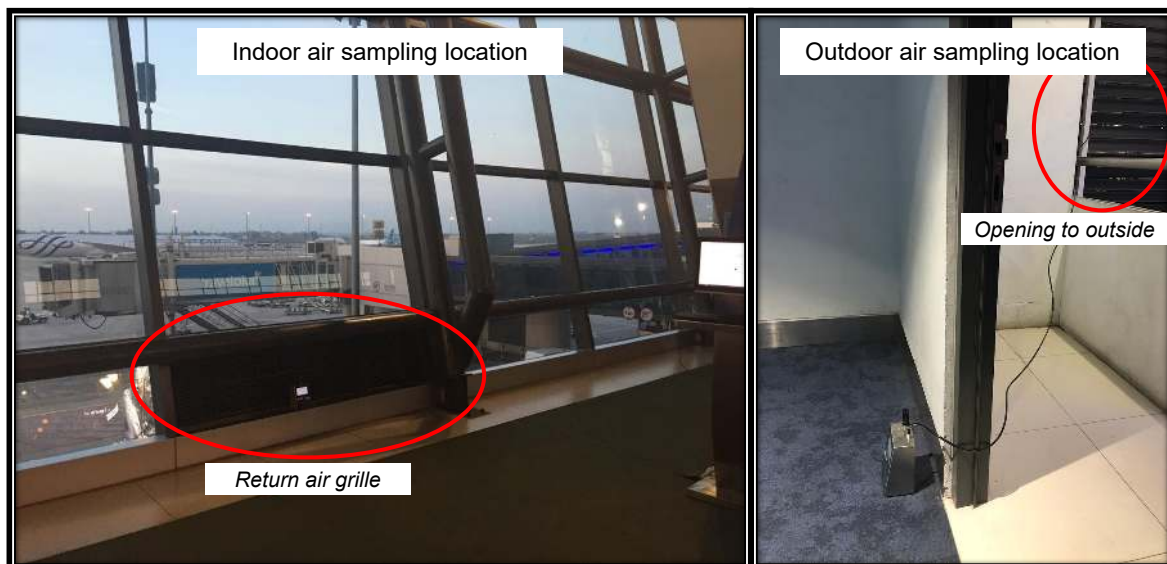**Figure 2.** Flow chart of daily access to the study site.

Figure 3. Sampling locations of the indoor and outdoor air.

2.2.2. Secondary Data

The weather data at the airport were obtained from the Indonesia Meteorology, Climatology, and Geophysical Agency (BMKG) [28] at 1-h intervals, as well as from Weather Underground [29] in 30-min intervals. Data from Weather Underground were used for analysis given the finer resolution. Previous studies have shown that light-scattering particle measurement devices are subject to error at high relative humidities [30–32]. Therefore, the measurements conducted when outdoor relative humidity (RH) was above 90% were excluded from further analysis. The remaining measurement sessions were listed in Table 1. The total numbers of arriving and departing aircraft and passengers each hour were also provided by the airport.

The heating, ventilation, and air conditioning (HVAC) system at Terminal 3 operates 24 h a day throughout the week. The central air conditioning system includes the chillers, pumps, cooling towers, and air handling units (AHUs). Water, which is used as the medium, is cooled in the chiller unit and then distributed to the AHUs through the pumps. A blower on the AHU side supplies the cool air

to multiple rooms in the terminal with an average air exchange rate of 70,000 m^3/h. The central air conditioning system consists of five units with a capacity of 2100 ton of refrigeration each. The AHUs are equipped with Dacron$^{\circledR}$ filter rolls as well as framed and washable filter media. The Dacron$^{\circledR}$ filters have high resistance to stretching in both wet and dry environments as well as to chemicals and abrasion [33]. The framed filters are cleaned monthly at the minimum as part of the HVAC maintenance schedule and replaced every year or when they are worn out (see Figure 4).

Table 1. Terminal 3 air quality measurement schedule.

Session	Measurement Date	Arrive	Depart
I	2 February 2019	4:00 p.m.	10:00 p.m.
II	2 March 2019	6:00 p.m.	11:00 p.m.

Figure 4. Filters being cleaned at the terminal.

2.3. Data Analysis

2.3.1. Particle Mass Concentration Estimate

The particles sampled by the monitor were divided into three groups for analysis based on the particle diameter; i.e., PM$_1$, PM$_{2.5}$, and PM$_{2.5-10}$. The particle numbers recorded for each group were converted into mass concentration using the particle density of 2.2 g/cm^3, as reported by Hasheminassab et al. [34] in an ambient fine and coarse particles study conducted in Los Angeles. The calibration factor was kept at 1, as used by the manufacturer.

Because the actual air change rate of the terminal building was unknown, the mass concentration was averaged over a 15-min interval based on the requirement of the Indonesian National Standardization SNI 03-6572:2001 [35] and the Jakarta Green Building User Guide [36]; i.e., four air exchanges per hour for lobby and corridor areas. The 15-min average was then smoothed using a simple moving average; i.e., for each observation x_t at time t, the smoothed data point $\overline{x_t}$ is given by Equation (1):

$$\overline{x_t} = \frac{x_{t-1} + x_t + x_{t+1}}{3} \tag{1}$$

The smoothed indoor and outdoor mass concentrations of the different particle size groups are shown in Figures 5–7 for the two measurement sessions.
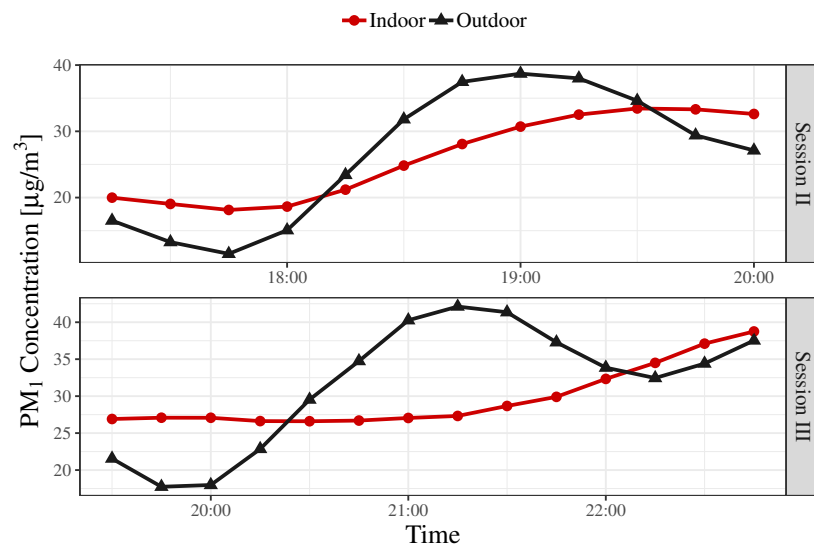

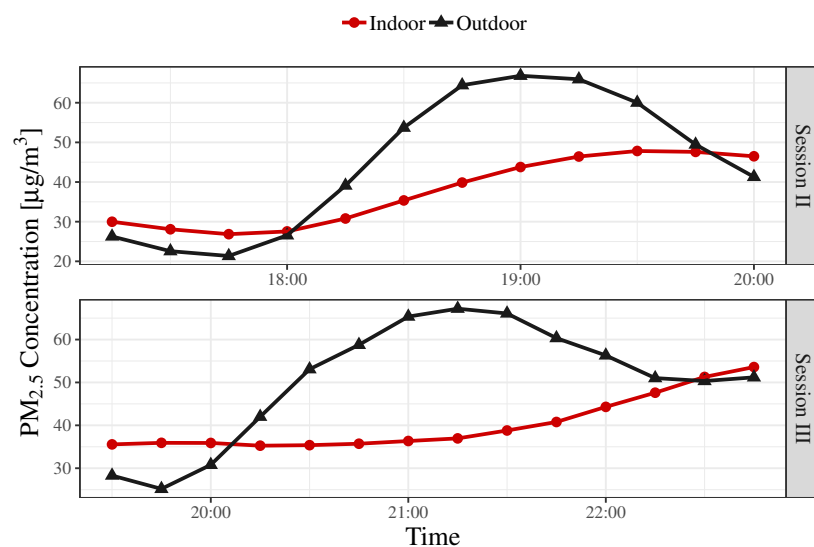**Figure 5.** Indoor and outdoor PM_1 mass concentration time series.

Figure 6. Indoor and outdoor $PM_{2.5}$ mass concentration time series.

2.3.2. Statistical Methods

The statistical tests and regression analysis presented in this paper have been conducted using R [37]. The indoor and outdoor PM concentration data were tested for normality using the Shapiro-Wilk normality test [38]. Based on the normality test results, the Paired Sample *t*-test or Mann-Whitney U test was used to compare the difference of indoor and outdoor PM concentration levels.

The effects of aircraft and passenger traffic on the indoor particulate concentration were evaluated using analysis of covariance (ANCOVA). The aircraft and passenger traffic were converted to categorical factors, whereas the indoor and outdoor PM concentrations were included as continuous variables.

The particle indoor/outdoor (I/O) ratio was calculated for PM_1 and $PM_{2.5}$ using linear regression. Given that the infiltration of outdoor particles is often not instantaneous [39–41], the regression analysis was performed with a time lag.
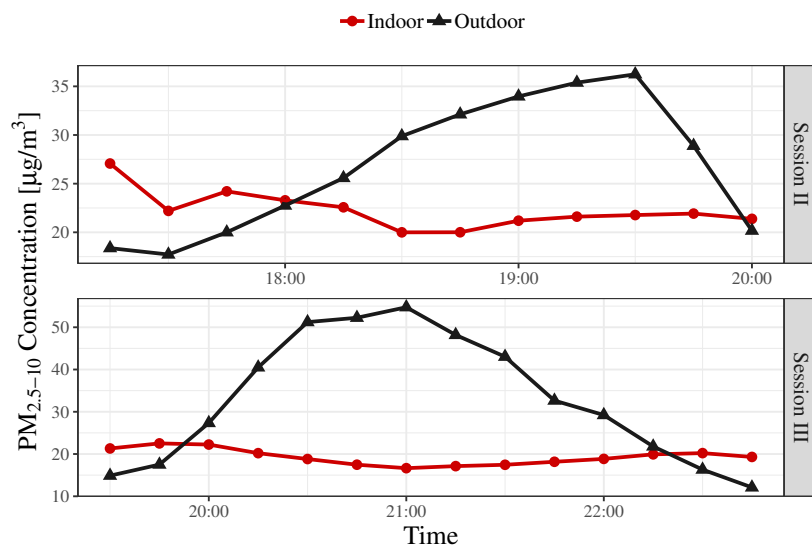
Figure 7. Indoor and outdoor $PM_{2.5-10}$ mass concentration time series.

3. Results

3.1. Descriptive Statistics

The descriptive statistics of the 15-min average mass concentration of the indoor and outdoor particles for the three size groups are summarized in Table 2 and also illustrated in Figure 8. The indoor and outdoor particle mass concentration data were tested for normality using the Shapiro-Wilk normality test [38]. The test statistic W and corresponding p-value are summarized in Table 3.

Table 2. Descriptive statistics of the indoor and outdoor particle mass concentration ($\mu g/m^3$).

Location	Particle Size	Min	Mean	Max	SD
Indoor	PM_1	18.13	28.04	38.75	5.54
	$PM_{2.5}$	26.85	39.00	53.59	7.47
	$PM_{2.5-10}$	16.65	20.67	27.07	2.39
Outdoor	PM_1	11.51	29.25	42.12	9.50
	$PM_{2.5}$	21.35	47.82	67.20	15.70
	$PM_{2.5-10}$	12.09	30.11	54.74	12.31

Table 3. Shapiro-Wilk normality test results.

Particle Size	Sample Size	Indoor		Outdoor	
		W	p-Value	W	p-Value
PM_1	26	0.955	0.298	0.920	0.045 *
$PM_{2.5}$	26	0.951	0.251	0.898	0.014 *
$PM_{2.5-10}$	26	0.966	0.528	0.941	0.140

* Normality hypothesis rejected at $\alpha = 0.05$.

Because the outdoor PM_1 and $PM_{2.5}$ were not normally distributed, the nonparametric Mann-Whitney U test (or Wilcoxon Rank-Sum test) was performed to examine the difference of mass concentrations between the indoor and outdoor PM_1 and $PM_{2.5}$, whereas the paired sample t-test was used for the indoor and outdoor $PM_{2.5-10}$. The Mann-Whitney U test showed no significant difference between indoor and outdoor PM_1 (p-value = 0.532). These particles are usually difficult to be filtered by the HVAC system, even with higher minimum efficiency reporting value (MERV) rated filters due to their small size. However, the indoor $PM_{2.5}$ and $PM_{2.5-10}$ particles appeared to be at a

much lower concentrations than outdoors, and the differences were statistically significant (PM$_{2.5}$: *p*-value = 0.008; PM$_{2.5-10}$: *p*-value = 0.002). This shows that the air filtration of the HVAC system in the terminal building was effective at removing particles between 1 μm and 10 μm in diameter.
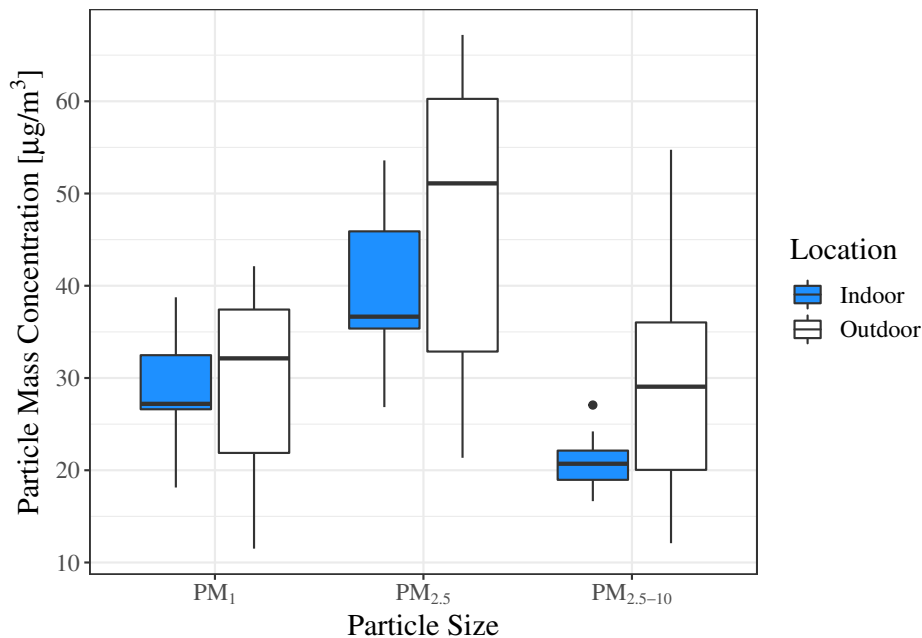

Figure 8. Comparison of indoor and outdoor particle mass concentrations of different size groups.

3.2. I/O Ratio

As illustrated by the time series in Figures 5–7, it was hypothesized that a time lag exists between the change of indoor and outdoor PM$_1$ and PM$_{2.5}$ concentration levels. However, no apparent correlation was observed in Figure 7 for PM$_{2.5-10}$. Cross-correlation of the indoor and outdoor PM$_1$ and PM$_{2.5}$ is shown in Figure 9, and the results suggest that the outdoor PM$_1$ lagged 15 min behind indoor values, whereas outdoor PM$_{2.5}$ lagged 30 min behind indoor values.
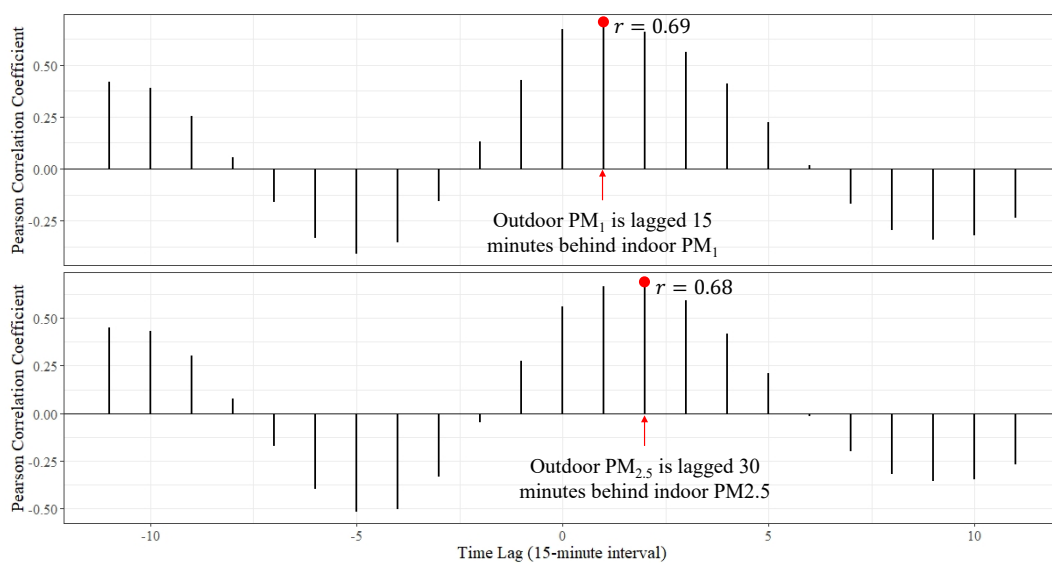

Figure 9. Cross-correlation of indoor and outdoor PM$_1$ and PM$_{2.5}$.

The I/O ratios for PM_1 and $PM_{2.5}$ were estimated using linear regression with the appropriate time lags. Using outdoor particle concentration x_t^{out} as a predictor, the indoor concentration x_t^{in} can be estimated using Equation (2):

$$x_{t+i}^{in} = a_0 + a_1 x_t^{out} \qquad (2)$$

where a_1 is the I/O ratio, a_0 is the contribution from indoor source, and i is the time lag in minutes.

Table 4 shows the estimated I/O ratios for PM_1 and $PM_{2.5}$. The variations of outdoor PM_1 and $PM_{2.5}$ concentrations appear to account for 41.6% and 32.5% of the change of indoor PM_1 and $PM_{2.5}$ concentrations respectively.

Table 4. Estimated I/O ratio using linear regression.

Particle Size	Time Lag (min)	Intercept	I/O Ratio	R^2
PM_1	15	16.357	0.416	0.521
$PM_{2.5}$	30	24.676	0.325	0.542

The traditional residential infiltration model (e.g., [39]) was not used in this study. That infiltration model was historically used for single family residences and took advantage of the fact that there were obvious indoor sources of PM, as seen by short-term peaks in the time series whose rising values were censored. However, in a large building such as an airport terminal, the indoor sources of PM_1 and $PM_{2.5}$ were not as obvious as in residences, and such sources were also diluted by relatively large volumes of building ventilation air. This was confirmed by the fact that the criteria for censoring of rising peak values used in the residential infiltration models [39] did not exclude any of the values observed in this study; i.e., there were no significant rising peaks in the data. Therefore it could not be assumed that the major effect of indoor source contributions over a given time period was removed, an assumption that was central to the censored infiltration model [39]. As an alternative, the association between the 15-min average indoor concentration and an appropriately lagged outdoor concentration was examined based on the results of cross-correlation analysis, as shown in Figure 9. This approach still provided insight into the significance of infiltrated outdoor PM on indoor PM levels with a limited amount of data.

3.3. ANCOVA

The effect of aircraft and passenger traffic on the indoor particle concentration was evaluated using ANCOVA. The total numbers of arriving and departing aircraft and passengers were converted to categorical factors, as defined in Table 5. Due to the relatively short data collection period, the creation of these categories was based on the traffic during the air quality measurement sessions (as marked in Figure 10) as opposed to the entire 24-h traffic volume.

Table 5. Aircraft and passenger traffic categories.

Category	Aircraft Traffic (movement/hour)	Passenger Traffic (movement/hour)
High	>12	>1200
Low	≤12	≤1200

Both "aircraft traffic" (impact from outdoor) and "passenger traffic" (impact from indoor) were categorical factors (as defined in Table 5). Given the time lags obtained between indoor and outdoor PM_1 and $PM_{2.5}$, and considering that the aircraft and passenger traffic data were only given in hourly totals, a one-hour lag was used for factor "aircraft traffic". The indoor and outdoor PM_1, $PM_{2.5}$, and $PM_{2.5-10}$ from the previous hour ($PM_{1,t-1}$, $PM_{2.5,t-1}$ and $PM_{2.5-10,t-1}$) were included as continuous variables. The ANCOVA results are shown in Table 6. It appears that "aircraft traffic" contributed significantly to the indoor fine particles PM_1 and $PM_{2.5}$, whereas "passenger traffic" had a significant influence on coarse indoor particles.
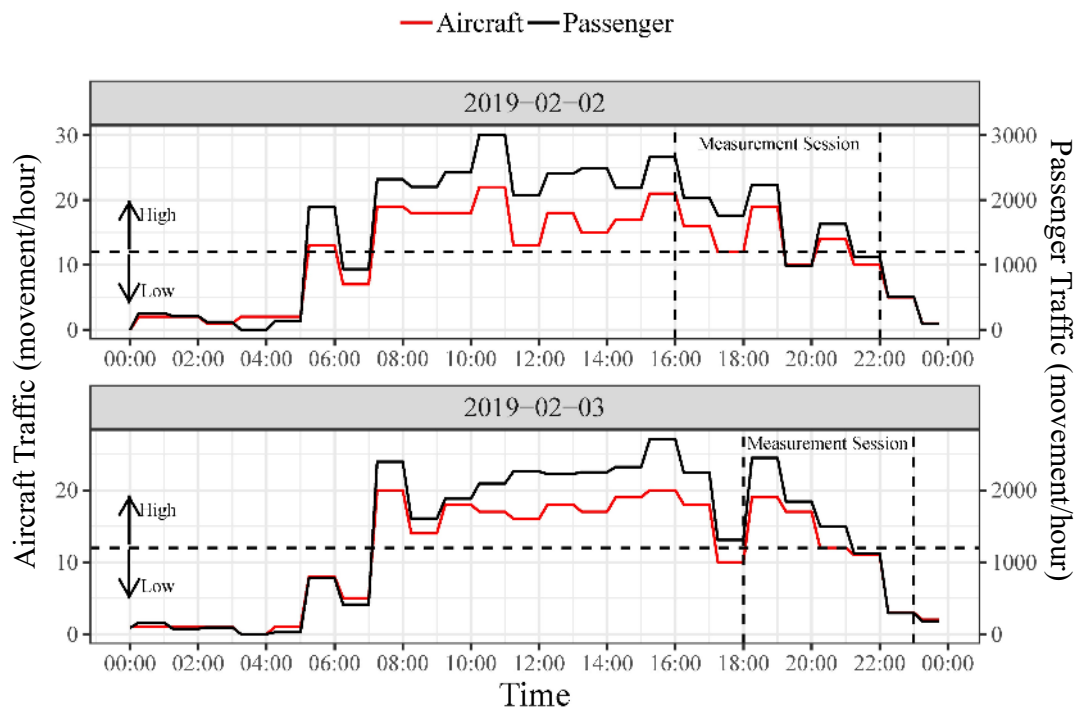
Figure 10. The aircraft and passenger traffic time series of the selected two days. The shaded area shows the period when air quality data were collected at the terminal.

Table 6. ANCOVA for the effects of aircraft and passenger traffic on indoor particle concentrations.

Particle Size	Factor	SS [†]	DF [††]	*p*-Value
PM$_1$	Outdoor PM$_{1,t-1}$	5.30	1	0.40
	Indoor PM$_{1,t-1}$	1.34	1	0.67
	Aircraft Traffic	34.06	1	0.05 **
	Passenger Traffic	8.83	1	0.29
	Residuals	93.03	13	
PM$_{2.5}$	Outdoor PM$_{2.5,t-1}$	12.65	1	0.41
	Indoor PM$_{2.5,t-1}$	4.81	1	0.61
	Aircraft Traffic	69.12	1	0.07 *
	Passenger Traffic	7.93	1	0.52
	Residuals	231.02	13	
PM$_{2.5-10}$	Outdoor PM$_{2.5-10,t-1}$	2.60	1	0.32
	Indoor PM$_{2.5-10,t-1}$	7.43	1	0.10 *
	Aircraft Traffic	2.18	1	0.36
	Passenger Traffic	16.57	1	0.02 **
	Residuals	30.99	13	

[†] Sum of squares; [††] degree of freedom; * the factor is significant at $\alpha = 0.1$; ** the factor is significant at $\alpha = 0.05$.

4. Discussion

The hypothesis tests showed that the indoor PM$_{2.5}$ and PM$_{2.5-10}$ were significantly lower than those outdoors, whereas the PM$_1$ concentration was comparable to the outdoor one. The estimated I/O ratios suggest that the air filtration system at the terminal was working effectively in removing PM$_{2.5}$ as compared to the reported ratios in Ren et al. [21]. However, the removal of PM$_1$ was less efficient. The ANCOVA results revealed that passenger traffic was a significant factor that affected the indoor coarse particle concentrations, while aircraft traffic showed significant effect on fine particles. The combined results indicate that the terminal building HVAC system is efficient at protecting the

passengers and employees from aircraft emissions and other outdoor particles. The change in indoor fine particle concentration was largely due to aircraft traffic, which was inevitable for an airport terminal building. On the other hand, the change in indoor coarse particle concentration was largely depending on the passenger movement and the concentration from the previous hour. This also reflects the ability of the coarse particles to remain in the building at the current air exchange rate. The additional air filtration and cleaning system inside the boarding bridge may reduce the particles brought into the terminal building by arriving passengers. Increased ventilation rate could also aid the removal of existing coarse particles in the terminal building. As summarized in [42], other than the PM of outdoor origin, there were numerous potential indoor sources of PM. For a large and complex building such as the airport terminal, these sources include particle emission and resuspension, which were often linked to human activities [42]. Studies have shown that bioaerosols emitted from damp surfaces, cleaning product residues, and cooking activities could contribute to indoor PM [42]. Particle resuspension from activities such as walking and vaccuming, which are common for a terminal building, is also an important source of indoor PM [14,15,43]. The indoor measurement conducted in this study was at a single location near the boarding gate. Therefore the main activity considered was the walking of passengers and the spatial coverage was rather limited. If resources permit, future studies could consider deploying multiple sensors at various representative sites inside the terminal to investigate the different PM contributions from different locations with various activities.

This study detailed the process of gaining access to the airport terminal building to conduct air quality measurements and could be beneficial to future studies at airports. Due to time and resource constraints, the measurements were only for a short period of time and the dataset was limited. Because the PM measurements were conducted using a light scattering monitor, the high level of humidity in Jakarta also resulted in data loss. The influence of humidity on the remaining optical measurements was evaluated by calculating the I/O ratios for subsets of the data with different RH cutoff values, and the results showed modest changes for the I/O ratios. In addition, as can be seen from Figure 10, the peak traffic periods were not covered by this study. A permanent air quality monitoring program at the airport would allow data collection in longer terms and contributes to the growth of the airport indoor air quality knowledge base.

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