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A multivariate study for characterizing particulate matter (PM_{10}, $PM_{2.5}$, and PM_1) in Seoul metropolitan subway stations, Korea

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HIGHLIGHTS

- We have monitored the concentration of particulate matters (PM_x) (i.e., PM_{10}, $PM_{2.5}$, and PM_1) in six major transfer stations.
- Outdoor PM_{10} is the most significant factor in controlling indoor PM concentration
- The station depth and number of trains passing through stations were found to be additional influences on PM_x.
- Principal component analysis (PCA) and self-organizing map (SOM) were employed to investigate external and internal factors.

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ABSTRACT

Given that around eight million commuters use the Seoul Metropolitan Subway (SMS) each day, the indoor air quality (IAQ) of its stations has attracted much public attention. We have monitored the concentration of particulate matters (PM_x) (i.e., PM_{10}, $PM_{2.5}$, and PM_1) in six major transfer stations per minute for three weeks during the summer, autumn, and winter in 2014 and 2015. The data were analyzed to investigate the relationship between PM_x concentration and multivariate environmental factors using statistical methods. The average PM concentration observed was approximately two or three times higher than outdoor PM_{10} concentration, showing similar temporal patterns at concourses and platforms. This implies that outdoor PM_{10} is the most significant factor in controlling indoor PM concentration. In addition, the station depth and number of trains passing through stations were found to be additional influences on PM_x. Principal component analysis (PCA) and self-organizing map (SOM) were employed, through which we found that the number of trains influences PM concentration in the vicinity of platforms only, and PM_x hotspots were determined. This study identifies the external and internal factors affecting PM_x characteristics in six SMS stations, which can assist in the development of effective IAQ management plans to improve public health.

1. Introduction

With about eight million commuters each day, the Seoul metropolitan subway (SMS) system has been a vital mode of transportation in the Seoul metropolitan area. SMS system is a vast network, with new lines being added continuously. Its number of users has remained remarkably consistent throughout its lifespan due to its convenience, capacity, and energy-saving efficiency.

Although subway system offers great advantages in metropolitan cities, it also suffers from indoor air quality (IAQ) problems, particularly in underground subway stations, causing the concerns on public health. In the case of the SMS, some stations are equipped with real-time tele-monitoring systems (TMS) for measuring the indoor air pollutants (NO, NO_2, PM_{10}, $PM_{2.5}$, CO and CO_2), and the data set collected was used to develop the prediction model [1] and validate IAQ sensors [2]. Feng et al. [3] reported the risks generated from carbonyl compounds analyzed in Shanghai's subway system. Previous study has reported, the major chemical species of underground subway particles to be Fe-containing species [4], and airborne particles collected by permanent magnets, so called magnetic particles, turned out to be iron metal at underground station of the SMS [5]. In particular, the concentration and properties of

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the particulate matter (PM) have attracted much public attention. Previous in vitro toxicological studies have demonstrated cytotoxicity, damage to DNA, and the inhibition of the immune system caused by PM [6–7]. Public health related studies have reported an increase of cardio-respiratory illnesses and morbidity, and a decreased life expectancy in individuals who have been exposed to PM [8–9]. Some studies have even warned that subway PM is more toxic than other types [7,10]. In underground subway stations, the concentration of PM_x, including PM_{10} and $PM_{2.5}$ size fraction, is known to be higher than in outdoor environment. This finding was observed to be the case in Seoul [11], and is consistent with previous studies undertaken in other metropolitan cities worldwide such as London [12], Helsinki [13], Los Angeles [14], Tokyo [15], Barcelona [16], Rome [17], Mexico City [18], and Shanghai [19]. Even so, other studies conducted in the same countries have reported lower concentrations of PM_x in underground subway stations [20]. This discrepancy is probably due to complex underground interior factors related to train operation including dust re-suspension, floor cleaning [21], the structure of tunnels [22], the ventilation system [23], and the traffic of trains [15], as well as the wear of steel and brakes [24]. In addition, PM concentration is dependent on not only temporal factors such as rush hour, weekend traffic, and seasonal air conditions [25–26], but also on spatial factors such as monitoring locations (i.e., different locations at platforms) [22–23] and the installation of platform screen doors (PSDs) [27]. In contrast to interior factors, a limited number of studies have sought to describe the relationship between the concentration of underground PM_x and exterior factors. Adams et al. [28] found a positive correlation between indoor PM concentration and above-ground wind speed. Since most studies consider only a limited number of factors affecting the PM concentration, our understanding of indoor PM concentration in subway stations is very limited. In Seoul, the recent changes in weather patterns, the incidence of Asian (yellow) dust and the frequent high concentration of fine particles in the air, has brought about the necessity of a comprehensive investigation into the relationship between indoor PM concentration and environmental factors.

The objective of this study was to analyze the PM_x (i.e., PM_{10}, $PM_{2.5}$, and PM_1 size fraction) concentration patterns of six major transfer stations in the SMS for three weeks during three seasons, and then to conduct a correlation analysis between the concentration of PM_x and multivariate environmental factors using principal component analysis (PCA) and self-organizing map (SOM). The environmental factors considered include indoor radiant temperature, CO_2, wind speed, temperature, and humidity, and outdoor PM concentration.

2. Materials and methods

2.1. Subject details

The six transfer stations with the greatest number of users (A1, A2, B1, B2, C1, and C2) were selected for monitoring IAQ. The daily mean range of passenger ridership was reported to be from 8984 to 34,880 in the six stations. The oldest station, A1 was opened in 1974, whereas C2, the most recently constructed station, has been in operation since 2011. Fig. 1 is a schematic illustration of the six stations monitored in this study, and their specifications are described in Table 1. Of these stations, the respective depth of concourse and platform of A1 are 4 and 9.8 m, and the deepest station of C2 is 18.6 and 23.1 m underground. In most stations, the platform is a facing one with the exception of stations A2 and B2, which have island platforms. In a facing platform, passenger platforms are located on both sides of the tracks, whereas in an island platform, passenger platforms are located between the two tracks.

PSDs were installed in all stations to block the direct air draft generated by train operation. All stations are equipped with a central mechanical ventilation system that pulls down air from the surface and releases it from the station through street-level openings. Also, all stations have the medium level of air filter in the air handling unit (AHU) which removes PM from the circulating air; but the performance of the air filtration system is not very efficient due to its low air tightness. It appears that the outdoor PM entered the station not only through the ventilation systems, but also through the elevator system, wayside gates, etc. During the monitoring, the mechanical ventilation systems were being operated from 7 am until 10 pm at stations A1, A2, B1, and C1; from 7 am until 9 pm at station B2, and from 5 am until midnight at station C1, respectively. Cooling air was also supplied during the summer. The cooling air systems had the same operating times as the mechanical ventilation systems, and the temperature was maintained above 28 °C. Whereas the majority of stations operated their mechanical

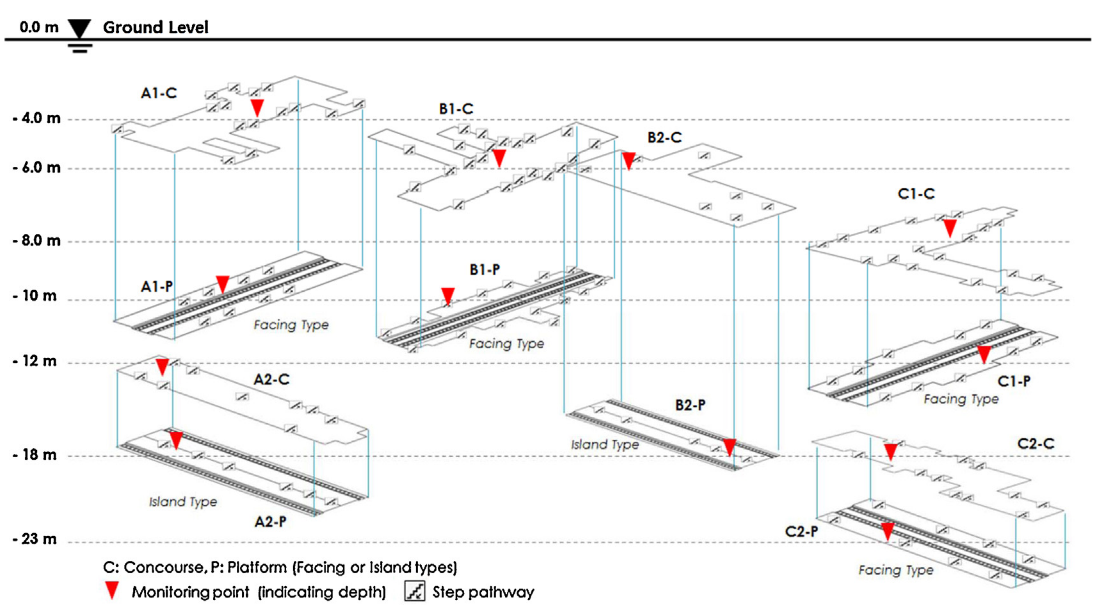

Fig. 1. Schematic illustration of monitored subway stations.