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Revitalizing subterranean spaces: a comprehensive study on enhancing air quality in underground shopping malls for sustainable urban living

Kichul Kim[1,2], Jiwoong Kim[2], Yun Gyu Lee[2], Seunghwan Wi[3] and Sumin Kim[1*]

Abstract

Cities worldwide are increasingly turning to underground spaces to address the challenges posed by high population density. These subterranean areas are now utilized for various purposes such as offices, shopping malls, subway terminals, and underground sidewalks. However, the semi-closed nature of most underground spaces presents difficulties in ensuring a comfortable environment due to the lack of natural ventilation. This study focuses on a representative underground shopping mall in South Korea, utilizing preliminary surveys and long-term sensor monitoring to identify existing problems. The aging ventilation system was retrofitted to enhance and assess indoor air quality. As a result, concentrations of carbon dioxide, total volatile organic compounds, and radon were reduced by over 33, 74, and 98%, respectively, while particulate matter with a diameter of 2.5 µm or less ($PM_{2.5}$) concentrations remained the same as before. This not only contributed to maintaining proper indoor air quality, but also led to a reduction in total energy consumption. The goal of this project is to improve air quality in facilities located in underground spaces, such as underground shopping malls, where indoor air quality management is challenging, thereby creating a safe and healthy environment for users and enhancing the overall functionality of the facility.

Keywords Indoor air quality, Underground space, Ventilation systems, Pollutant concentrations, Long-term monitoring

1 Introduction

Degradation of indoor air quality (IAQ) can have several negative effects, such as health consequences. Therefore, improving IAQ has become increasingly important in countries such as Korea. At present, people spend more than 80–90% of their time in indoor spaces for both residential and working purposes [1]. Consequently, poor indoor environments in buildings negatively affect the occupants' health, which is now regarded as a major social issue in Korea [2]. According to the World Health Organization, air contaminants lead to approximately 7.3 million deaths every year worldwide, of which indoor air contaminants account for approximately 4.3 million deaths [3].

As $PM_{2.5}$ concentrations continue to rise in Korea, so seems to be the interest of citizens in IAQ. This social awareness has also extended to the IAQ of multi-use facilities, particularly underground shopping malls. Underground shopping malls are generally located in

*Correspondence:
Sumin Kim
kimsumin@yonsei.ac.kr
[1] Department of Architecture and Architectural Engineering, Yonsei University, Seoul 03722, Republic of Korea
[2] Department of Building Research, Korea Institute of Civil Engineering and Building Technology, Goyang 10223, Republic of Korea
[3] School of Architecture, Seoul National University of Science and Technology, Seoul 01811, Republic of Korea

semi-closed basements, making it difficult to manage their air quality, for example, via ventilation; hence, the interest in controlling the IAQ of underground shopping malls has increased significantly in recent years [4].

The Korean metropolitan area (i.e., Seoul-Si, Gyeonggi-Do, and Incheon-Si) has a population density of 16,700 km^{-2}, ranking 6th among the world's major cities; moreover, it is known as one of the countries facing severe air pollution problems due to high levels of $PM_{2.5}$ and other pollutants [5]. Environmental problems are generally attributed to a high population density, which in turn implies that there is a saturation of transportation networks as well as restrictions on the availability of land and urban supply facilities [5]. Therefore, solutions to the shortage of space owing to the lack of land resources and overpopulation in metropolitan areas are needed urgently [6]. This is particularly true for the densely populated Korean metropolitan area, which also has 28 subways.

In this context, cities worldwide that are experiencing the problems are formulating plans to utilize underground space. The underground sector has several advantages, including conservation of space [7], good thermal efficiency [8] resistance to external noise [7], and safety from natural disasters. However, it also has certain disadvantages, such as high construction cost [9], poor ventilation (i.e., air circulation) [9], and lack of public acceptance [10]. At present, several initiatives are being taken to utilize underground spaces by addressing their shortcomings and maximizing their strengths in Southeast Asia. In China, the urban underground space plan was proposed in 1997 to develop and utilize underground space [11], for example, underground water reservoirs have been built using underground coal mines [12], underground spaces have been utilized for transportation purposes, and underground commercial buildings have been constructed [13]. In Japan, underground spaces have been mainly devoted for public use. This is because underground walkways, shops, and offices exhibit excellent soundproofing, earthquake resistance, and can also maintain a constant temperature and humidity; hence, underground construction is expected to continue actively in Japan [14].

Underground spaces in Korea are mainly used for constructing large shopping malls, which are well connected by subways or bus terminals for the ease of shoppers [15]. Although there is a growing trend in Korea to solve problems related to land shortage and overpopulation by utilizing underground spaces, these should not be utilized solely based on their advantages. Safety measures against fires and earthquakes [16] in underground spaces should be considered carefully as they are likely to be different from those invoked for surface facilities. However, the most important factor to be considered is the IAQ, which directly affects the health of the citizens. In particular, special management is needed for citizens who stay in underground spaces for more than 12 h.

Unlike aboveground spaces, the quality of air in underground spaces is particularly dangerous. In general, it is difficult to achieve proper air circulation in closed underground spaces due to the absence of natural ventilation. In addition, stagnation of pollutants such as toxic gas and $PM_{2.5}$ due to insufficient or defective ventilation may cause severe health problems for long-term residents and users of underground spaces. Nevertheless, there is currently no standard for measuring the air quality of underground spaces by considering seasonal variations or many people who use that spaces; moreover, air pollution due to $PM_{2.5}$, Carbon dioxide (CO_2), unpleasant odors, and radon (Rn) is on the rise due to the lack of proper ventilation [17]. Indoor pollutants in underground spaces have a harmful effect on the human body. Because $PM_{2.5}$ is relatively small in diameter, it enters the body through the airway and penetrates deeply into the alveoli, causes chronic bronchitis, and can lead to death if exposed to high concentrations for a long time [18]. CO_2 is a colorless and odorless gas that generally causes headaches and blood pressure to rise as a major indicator of indoor air pollution, and when exposed to high concentrations of 50,000 ppm or more, it becomes a fatal state due to confusion of consciousness [19]. Rn, a by-product of radium produced by the continuous decay of uranium (or thorium) contained in natural materials such as soil or rocks, is a colorless, tasteless, and odorless radioactive gas that has a risk of causing lung cancer [20]. Rn presence was reported mainly in indoor environment, soil and water. Among them Rn concentration is predominant as bed rocks and soil emanates high concentration of radium. Because of constant dispersion and dilution, Rn and its decay products rarely reach high levels outdoors. Therefore, Rn is considered as one of the major indoor air pollutants. As people spend more time indoor, high indoor Rn pollutant creates a threat for humans. Comparing indoor and ambient air, Rn concentration is found higher in indoor environment [21]. Underground shopping malls require management because the risk of exposure to Rn is high due to the nature of the space located underground. In September 2006, large quantities of CO leaked from the Jonggak Underground Shopping Center in Korea—hundreds of people were evacuated urgently and approximately 60 merchants and pedestrians were admitted to hospitals. The leakage was later attributed to defects in the air conditioning system. This incident raised significant awareness regarding the air quality of underground spaces in Korea [22]. Note that most of the underground spaces in Korea are connected to subways, which are further responsible for polluting the underground air; moreover, underground stores sell a variety of goods, which in turn increases the risk of underground air pollution [23].

In general, it is difficult to control the temperature and air quality of underground shopping malls, which is compounded by the lack of awareness regarding the same [24]. There are 25 underground shopping malls (having a total of 2,788 stores) in Seoul alone and the IAQ is not being properly managed in most of them due to various factors. For instance, the Seoul Facilities Corporation only checks whether the air quality maintenance/recommendation standards are met by all the underground shopping malls located in Seoul once a year. Although it has been reported that the three major air pollutants, namely CO_2, Formaldehyde (HCHO), and Carbon Monoxide (CO), meet both the national and Seoul standards [25], actual user satisfaction regarding the air quality of underground shopping malls is very low [6]. Therefore, IAQ is an important factor that needs to be considered before constructing underground facilities, as it closely impacts public health; however, large-scale empirical studies on the improvement of IAQ in underground shopping districts are still lacking.

The aim of this study is to improve the IAQ by retrofitting the aging ventilation system of underground shopping malls. To this end, we evaluated the IAQ of underground shopping malls using retrofitted ventilation systems while accounting for the actual number of shoppers. Recently, the importance of indoor ventilation has increased significantly owing to the COVID-19 pandemic. There is also an increasing concern regarding the ventilation of enclosed underground spaces, which would require special management [26].

In this study, we identified the primary problems in advance and accordingly conducted surveys on representative underground shopping malls in Korea. The IAQ of these underground shopping malls was improved by installing retrofit ventilation systems and sensors for long-term monitoring. As mentioned earlier, the IAQ of underground spaces is different from that of aboveground spaces owing to various factors, such as air circulation and natural ventilation. To this end, in this study, we conducted a preliminary investigation of the IAQ of underground shopping malls, following which the corresponding IAQ status was determined; we also conducted long-term monitoring of the IAQ by installing IAQ sensors. We achieved our objective by retrofitting the ventilation systems of underground shopping malls and performed a comparative evaluation of the IAQ both before and after the remodeling. The results of this study are expected to contribute to the development of essential guidelines for improving the IAQ of underground spaces in general.

2 Methodology

To investigate the impact of improving ventilation systems on IAQ in underground spaces, the study was conducted using the following methods: Firstly, selecting the target facility and examining its characteristics. Secondly, conducting a survey to assess the IAQ perceptions of merchants and users in the target facility. Thirdly, defining methods for measuring IAQ and discussing data processing techniques for analysis. Fourthly, outlining approaches to retrofitting ventilation systems to improve IAQ.

2.1 The target facility: Gangnam underground shopping mall

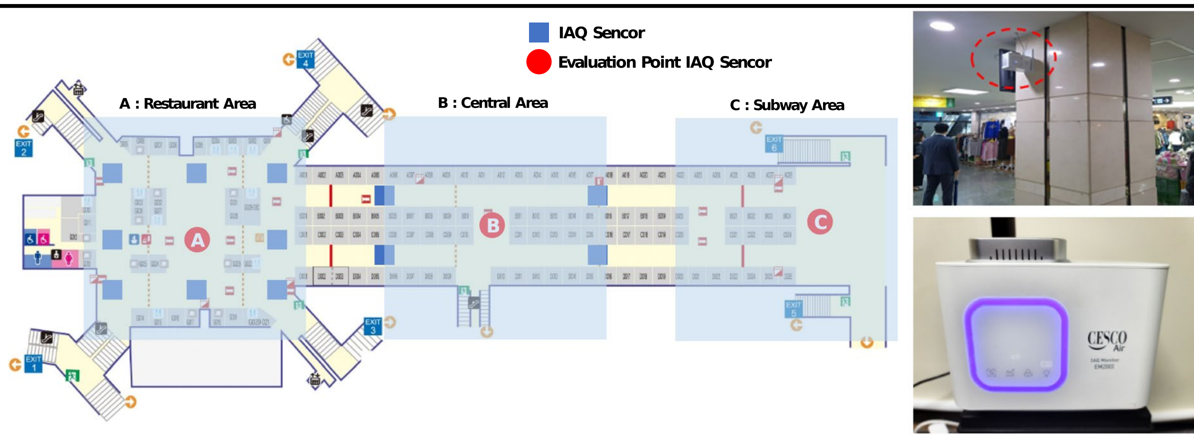
It was evaluated the IAQ of a typical underground shopping mall in Korea. $PM_{2.5}$ and CO_2 were selected as the representative pollutants typically present in underground shopping malls. After retrofitting the ventilation system and performing long-term monitoring, we accurately measured the change in the IAQ of the underground shopping mall. We employed the IAQ management method proposed by the Ministry of Environment, Korea. The underground shopping mall is managed with PM_{10} below 100 μg m^{-3}, $PM_{2.5}$ below 50 μg m^{-3}, CO_2 below 1000 ppm, HCHO below 100 μg m^{-3}, CO below 10 ppm, Nitrogen Dioxide (NO_2) below 0.1 ppm, Rn below 148 Bq m^{-3} and Total Volatile Organic Compounds (TVOC) below 500 μg m^{-3}.

We studied the Gangnam underground shopping mall as a typical example of an underground shopping mall in Korea. It has a total area of 31,566 m^2 and consists of 620 stores, as shown in Table 1. Clothing, flowers, household goods, and restaurants are the main industries in this shopping mall. The shopping mall is connected to Seoul Subway Lines 3, 7, and 9. The Gangnam underground shopping mall is characterized as a class 4 A climate zone (mild–humid) according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard [27].

The ventilation system of the Gangnam underground shopping mall consists of simple supply and exhaust fans in the stores and passageways and 17 auxiliary devices, such as air purifiers. The air conditioning system operates 24 h d^{-1} with an efficiency of 70%; however, several complaints have been raised against the noise generated owing to the lack of space in the ceiling where the air conditioning duct is located.

The daily average floating population of the shopping mall is about 20,000, with the highest footfall occurring at

Table 1 Gangnam underground shopping mall [25]



(a) Layout and IAQ sensor locations

Address	Sinbanpo-Ro, Seocho-Gu, Jiha 200
Size	Area 31,566 m^2; 620 stores
Management company	Goto Mall Co.
Operating hours	10:00 to 22:00 The passage is open 24 h (all year round)
Major industries	Clothing, flowers, household goods, restaurants
Connectivity	Seoul Subway Lines 3, 7, and 9 and express bus terminals connecting the entire city

2 pm (i.e., when the daily temperature is at its maximum) and during rush hours (i.e., 8:00–9:00 am and 6:00–8:00 pm). As for the measurement point, the central point (A) of the place where the restaurant is concentrated, the middle point (B) of the target site, and the point (C) affected by pollutants entering the subway direction were selected as representative points.

Research on the improvement of IAQ in Korea's representative underground shopping malls is expected to have important implications for all underground shopping malls, especially those that are experiencing difficulties in managing IAQ.

2.2 Preliminary IAQ assessment and survey

Surveys and actual measurements were conducted to identify the specific problems experienced by the representative underground shopping mall. Actual measurements of $PM_{2.5}$, CO_2, CO, TVOC, and HCHO were performed using IAQ sensors, whose locations are shown in Table 1. The survey aimed to first identify the problems of the underground shopping mall before improving the underlying ventilation system. A total of 161 people (30 Koreans, 30 foreigners, and 101 internal merchants), including both customers and merchants, were surveyed regarding the following: (1) interest in IAQ; (2) impact of indoor and outdoor air quality on health; (3) sensitivity to IAQ; and (4) IAQ evaluation. The survey was conducted in consideration of sex, age, usage time, and products sold for sellers. The subjective one was based on answers collection following ISO 10,551. The assigned values range between 1 and 5 for the five-point scale [28].

2.3 Data collection and preprocessing

To achieve the objectives of this study, indoor air pollution sensors capable of measuring 8 pollutants were installed in the Gangnam underground shopping mall, as shown in Table 1. Several representative locations (A: Restaurant area; B: Central passageway; C: Subway connection) were selected throughout the shopping mall to evaluate the IAQ. The IAQ was measured every 10 min using an integrated IAQ sensor (Model: EM2001 by CESCO(Seoul)). The measuring characteristics of the IAQ sensors were as follows. $PM_{2.5}$: ± 15 μg m^{-3} (0 to 100 μg m^{-3}); temperature: ± 0.2 °C (−10 to 80 °C); relative humidity: ± 1.5% (10 to 90% at 25 °C); Rn: ± 0.033 Bq m^{-3} (0.003 to 0.185 Bq m^{-3}), ± 13% (0.37 to 1.85 Bq m^{-3}); CO_2: 50 ppm + 3% reading value (0 to 5,000 ppm); and TVOC: ± 0.01% (0 to 1,187 ppb).

The present study lasted for approximately three years, from June 2018 to June 2020. The outdoor meteorological data was collected from the meteorological observatory under the Ministry of Environment (Air Korea initiative). Korea has four seasons: spring (march through May), summer (June through August), fall (September through October), and winter (November through February) [29]. The spring and fall seasons are characterized by high levels of yellow dust due to the prevailing westerly winds in the upper atmosphere, which are highly influenced by $PM_{2.5}$ from outdoors, and the winter season is characterized by low humidity, which makes it difficult to control indoor humidity, and the number of ventilations decreases due to cold weather.

In summer, the concentration of indoor pollutants is higher than in other seasons due to high temperature and humidity, and the need for ventilation increases. Due to the high temperatures of up to 38 °C in summer, people use underground shopping malls a lot, so it is essential to maintain and improve the IAQ of underground shopping malls. In this study, the study was conducted based on the IAQ in June in consideration of the seasonal characteristics of Korea. Once the ventilation system of the underground shopping mall was retrofitted, the improvement in the IAQ was verified by long-term monitoring.

For long-term monitoring using sensors, considerations such as sensor protection, lifespan, and reliable data communication are crucial. This study was conducted in a facility frequented by various merchants and visitors, necessitating the installation of sensors in locations inaccessible to human interference for their protection. Regular maintenance, typically involving sensor verification and replacement every two years, was performed to ensure data reliability.

2.4 IAQ improvement technologies: retrofit ventilation system

The need for good ventilation systems in underground buildings has been recognized for a long time [30]. A good ventilation system ensures proper circulation of fresh air inside buildings and maintains the desired air quality level [31]. Aboveground buildings should be designed to properly open and close windows according to outdoor temperature to improve indoor ventilation [32], but Unlike aboveground buildings, underground buildings rely on mechanical ventilation systems because of insufficient openings to allow natural ventilation [6]. Good ventilation systems also dilute and remove pollutants from buildings and stabilize the indoor environment by facilitating adequate airflow under all conditions.

The Gangnam underground shopping mall was originally equipped with a mechanical ventilation system. However, the efficiency of this ventilation system was low owing to the use of regular fans (Fan efficiency grade (FEG)-60); in addition, the pressure inside the duct was high, which resulted in very low performance of the supply and exhaust fans at the duct end. Moreover, when the wind pressure at the entrance of the duct was high, the duct would ring when the ventilation system was running, and due to the unavailability of space in the ceiling where the duct was installed a lot of noise was generated, which further prevented the operation of the system at maximum efficiency. FEG is an indicator of the aerodynamic ability of a blower to convert axial or impeller power into air power. It is the sole criterion used for evaluating the efficiency of a blower irrespective of the efficiency of the motor/control system. FEG is based on the peak (optimal) efficiency of a given blower and is used to determine the energy use characteristics of the underlying ventilation system.

In this study, the fan efficiency, which was previously FEG-60, was retrofitted to the level of FEG-80. The fans in the original ventilation system were replaced with high-performance FEG-80 fans to improve the overall equipment efficiency and the duct was replaced to reduce the noise generated. FEG-80 showing the best efficiency was selected by comprehensively considering the energy efficiency of the fan itself and the required ventilation in the underground shopping mall.

The original ventilation system used a single main fan to ventilate the entire shopping mall, which put a lot of load on the main fan. The ventilation system was retrofitted, and the duct was reconstructed to minimize thermal energy loss and improve efficiency. The retrofitted system also reduced existing noise levels. In the retrofitted system the load on the main fan was substantially reduced and the ventilation performance improved significantly owing to the newly installed heat exchangers.

Booster fans were also installed to achieve uniform air supply and exhaust performance throughout the entire shopping mall. The booster fan installation location was selected according to the frequency and flow of indoor pollutants in each area, and the booster fan was distributed and installed locally to improve air quality in areas with significantly low pressure or high pollutants. The fan performance before and after installing the improved ventilation system was verified using Computational Fluid Dynamics (CFD) (Fig. 1), and static pressure, power and efficiency were improved overall. The retrofitted main and booster fans, installation sites are shown in Fig. 2. As shown in Fig. 2, the booster fan was installed in the A–F areas based on inspections using the underground shopping mall drawing (duct passage), and with this installation, the fresh air can be distributed evenly in indoor spaces.

The structure of the retrofitted ventilation system was such that it could easily replace the original ventilation system. Moreover, the performance of the retrofitted ventilation system improved significantly as demonstrated by the simulation results. Note that the booster fans were manufactured in the clean interior of the underground shopping mall and were installed to reduce the overall noise generated.

The comprehensive retrofit of the ventilation system includes redesigning the main fan axial blades, determining the optimal shape of the inlet using CFD analysis, designing the casing to maintain pressure (including bearing strength and shaft strength design), energy savings, and designing booster fan impellers for uniform air distribution.

3 Results and discussion

3.1 Preliminary IAQ assessment and survey results

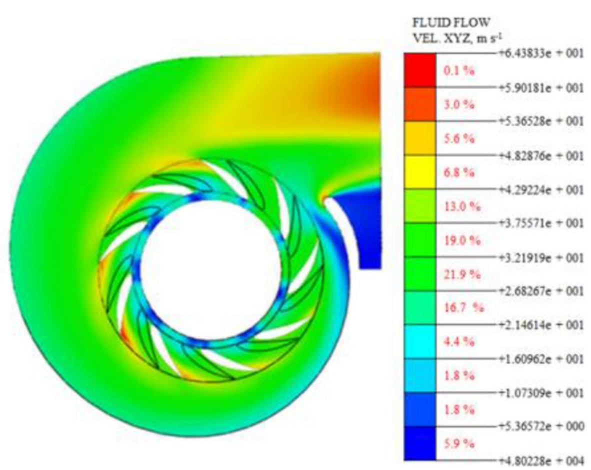
Before the ventilation system was retrofitted, a survey was conducted on customers and merchants to identify the problems concerning the IAQ of the Gangnam underground shopping mall, following which precise measurements were performed to gauge the actual status.

The survey was conducted on a total of 161 people, including 60 customers and 101 internal merchants. Among the survey participants, 53 were men and 108 were women, with about 28% of the participants being in their forties. Most of the customers visited the shopping mall during afternoon hours, and most of the merchants had 6–10 years of store management experience. The stores mainly sell clothing, shoes, accessories, bedding, and general goods. Figure 3 shows the typical characteristics of the survey.

The survey questions were regarding the following: interest in IAQ, sensitivity to harmful substances in the indoor air, and IAQ level in the Gangnam underground shopping mall. The survey showed that more than half of the respondents were interested in IAQ and sensitive to harmful substances. In addition, more than 80% of the respondents thought that the air quality in underground shopping malls adversely affected their health and that proper management is necessary. The indoor environment of the Gangnam underground shopping mall was reported to be hot and dry along with the presence of fine dust and unpleasant smells. In particular, the mean score of the IAQ level was below average and Koreans, who use underground shopping malls more often than foreigners, rated it even lower. Overall, the customers and internal merchants rated the air quality of the Gangnam underground shopping mall to be below average and most of them were aware of the need for a retrofit ventilation system. The survey results are summarized in Table 2.

(a)

Flow rate ($m^3 h^{-1}$)	Static pressure (Pa)	Power (kW)	Efficiency (%)
65,000	19,998	49	64.9



(b)

Flow rate ($m^3 h^{-1}$)	Static pressure (Pa)	Power (kW)	Efficiency (%)
67,000	19,998	43	71.5

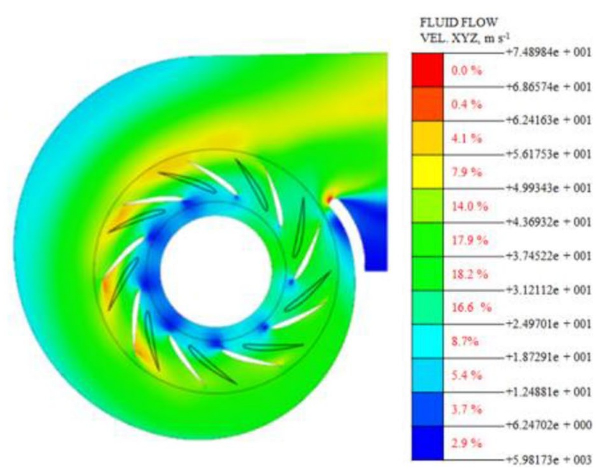


Fig. 1 Evaluation of the main fan performance using CFD (**a** before improvement; **b** after improvement)

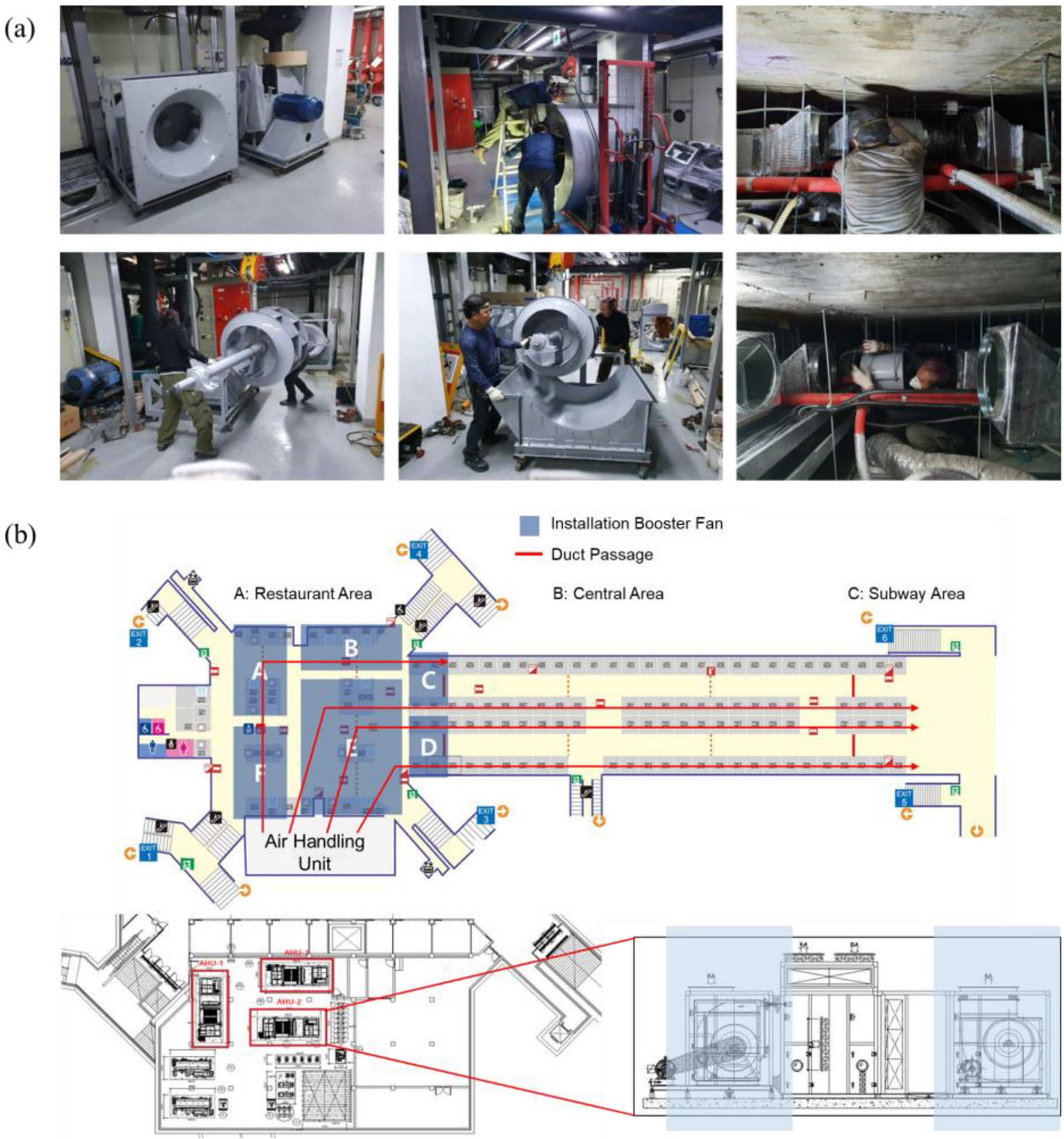


Fig. 2 Installation site and location of the retrofit ventilation system (**a** installation site; **b** installation location)

Actual measurements of the pollutants CO_2, CO, $PM_{2.5}$, TVOC, HCHO, Rn, and NO_2 were conducted from June 25 to June 29, 2018. The locations of the measurements were divided into three zones: restaurant district (A), central passage area (B), and subway-linked area (C). Actual measurements were conducted in accordance with Ministry of Environment Indoor Air IAQ Quality Test Standards (KS ISO 16000). We found that the average CO_2 concentration exceeded the recommended value in zone B, whereas the fine dust concentrations were well within the recommended values. The recommended values were observed to exceed in zone C during the mornings and evenings. In addition, the concentration of TVOC was significantly higher than the recommended standard in both zones A and B. The results of pre-actual measurement of IAQ are shown in Table 3.

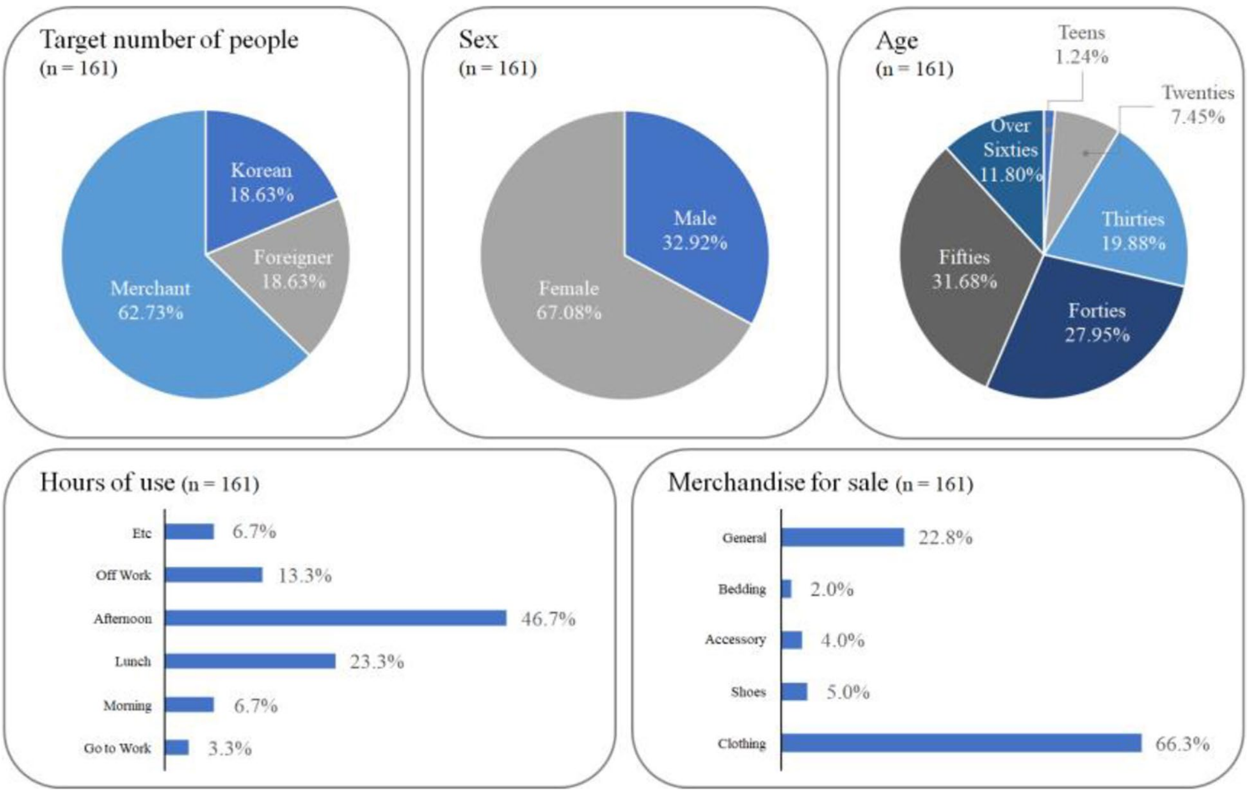


Fig. 3 Survey characteristics

Table 2 Survey results

	Very low (Score)	Low	Normal	High	Very high	Total Score (Highest = 5)
Interest in indoor air quality						
Korean (*n* = 30)	0.00	0.13	0.80	2.53	0.16	3.63
Foreigner (*n* = 30)	0.03	0.20	0.80	1.87	0.67	3.57
Merchant (*n* = 101)	0.02	0.08	0.77	2.18	0.70	3.75
Sensitivity to hazardous substances						
Korean (*n* = 30)	0.00	0.13	0.60	2.93	0.00	3.67
Foreigner (*n* = 30)	0.03	0.53	0.40	1.73	0.67	3.36
Merchant (*n* = 101)	0.00	0.06	0.92	2.30	0.45	3.72
Indoor air quality level						
Korean (*n* = 30)	0.00	1.20	0.80	0.53	0.00	2.53
Foreigner (*n* = 30)	0.03	0.20	1.70	1.07	0.17	3.17
Merchant (*n* = 101)	0.03	0.71	1.10	0.99	0.00	2.83
Indoor air quality evaluation						
Korean (*n* = 30)	0.23	1.40	0.20	0.00	0.00	1.83
Foreigner (*n* = 30)	0.13	1.27	0.70	0.00	0.00	2.10
Merchant (*n* = 101)	0.11	0.73	1.43	0.20	0.00	2.47

3.2 Characteristics of the retrofit ventilation system

The ventilation system was retrofitted to improve the IAQ in the Gangnam underground shopping mall. The original ventilation system not only used low-efficiency supply and exhaust fans but also exhibited very low performance at the duct end due to the high pressure inside

Table 3 Actual measurements of the indoor air quality

Zone	CO_2 (ppm)	CO (ppm)	NO_2 (ppm)	PM_{10} (μg m^{-3})	$PM_{2.5}$ (μg m^{-3})	$PM_{1.0}$ (μg m^{-3})	TVOC (μg m^{-3})	Rn (Bq m^{-3})
A	851	0.038	0.02	21	17	16	833	27
B	977	0.053	0.03	25	14	13	730	33
C	927	0.047	0.03	31	13	11	482	36

Table 4 Specifications of the upgraded supply and exhaust fans

Characteristics	Values	Note
Supply/Exhaust Fan		
air volume	45,000 m^3 h^{-1}	29% better than before
positive pressure	16 kPa	
efficiency	80%	
FEG	80 Class	
power	26 kW	
Booster Fan		
air volume	3,000 m^3 h^{-1}	-
noise	70 dB/A or less	

the duct. The original system also generated a lot of noise. Consequently, the energy consumption was high because the ventilation system operated 24 h d^{-1} at an efficiency of only 70% to maintain the IAQ.

The FEG-60 supply and exhaust fans in the original ventilation system were replaced with high-performance FEG-80 fans; in addition, a booster fan was installed at an appropriate location to enhance the performance of the supply and exhaust fans. The upgraded high-efficiency FEG-80 fans had the following specifications: air volume = 45,000 m^3 h^{-1}, positive pressure = 16 kPa, voltage efficiency = 80%, and impeller size = 900 mm. The booster fan was installed at a location with a very low feed/exit performance; in addition, it had an air volume of up to 3,000 m^3 h^{-1} and generated noise less than 70 dB/A. The upgraded fans improved the IAQ by more than 29% and the energy consumption was also reduced owing to the flexible operation of the ventilation system. The basic specifications of the upgraded supply, exhaust and booster fans are shown in Table 4. The pre-filter (equal to or better Minimum Efficiency Reporting Value (MERV) 7) and medium filter (equal to or better MERV 15) were used for the retrofitted ventilation system. Air filter performance was calculated using the ASHRAE Standard 52.2–2017 test method [33] using the air volume at the filter inlet and outlet.

Owing to the improvement of the ventilation system and installation of booster fans, uniform performance of the supply and exhaust fans was achieved throughout the entire underground shopping mall. Moreover, the smoothly operating ventilation system resulted in proper IAQ maintenance and significant reduction in energy consumption.

The constant air volume of the main fan was set in the range 45,000–49,000 m^3 h^{-1}, while the diffusers had an air volume of 500 m^3 h^{-1} and wind velocity of 2.5 m s^{-1}. A total of 250 mm diffusers was installed in the stores and passageways of the shopping mall, which were linked to the supply and exhaust fans. The diffusers supplied fresh air from outside and simultaneously discharged pollutants from inside the shopping mall. The booster fan supplied an appropriate air volume to the terminal duct, thereby reducing the load on the main fan and minimizing the energy consumption. The retrofitted ventilation system meets the required ventilation rate for underground shopping malls in Korea (at least 36 m^3 cap^{-1} h^{-1}).

Energy savings potential in retrofit ventilation systems was calculated formula and then compared with the energy use in previous ventilation systems. The calculation results are shown in Table 5. The energy consumption in the previous system was 264 kWh, and the

Table 5 Energy savings calculation results

			Before application (kWh)	After application (kWh)	Energy saving (kWh)
Main fan	Fan efficiency	(Improving)	50	41	− 9
Booster fan	Power	(Additional installation)	-	48	+ 48
Heat exchanger	Thermal energy	(Evaluation)	214	112	− 102
Total			264	201	− 63

energy consumption after the system application was 201 kWh, which was about 24% of energy savings compared to the existing energy consumption. The primary energy-saving drivers are main fan power and heating and cooling energy reduction. The ventilation performance in the Gangnam shopping mall was measured using the installed sensors by considering the time of the day when the concentration of specific pollutants was high as well as the time when the floating population was large. The ventilation system was then operated based on these conditions to ensure optimum IAQ and energy consumption.

In the field of studying ventilation in underground spaces (shopping malls, buildings, tunnels, mines, etc.), most of them emphasize uniformity, ventilation efficiency, and energy consumption. Deng et al. [34] conducted a study on "Uniformity and energy evaluation of equal cross-section ventilation system (ECVS) for long tunnel in underground buildings". Through computational fluid dynamics numerical simulations, the effects of major duct speeds, aspect ratios, and outlet numbers on uniformity per unit air volume and energy consumption were analyzed. As a result, it was argued that uniform ventilation in the tunnel is an important factor for safety and is the easiest way to install large air ducts and provide uniform air to solve this problem, Mukhtar et al. [30] evaluated the concept of a building ventilation system and the evaluation of the IAQ level of building users as important factors among the factors for establishing an underground building design strategy [32]. In addition, Sittisak et al. [35] conducted a study to remove CO in an underground parking lot using jet fan ventilation. It was argued that the installation of a single inclined jet fan is the best way when considering ventilation efficiency and energy utilization [36]. Wang et al. [37] suggested that the ventilation system could have a direct effect on the $PM_{2.5}$ concentration of subway stations, and that it could be solved by providing sufficient air for the space size and environment proposed in this study and suggested a direction for IAQ in underground spaces.

The retrofitted ventilation system is designed to use pre and medium filters. While advanced air filtration technologies such as HEPA filters or electrostatic precipitators could enhance indoor air pollutant removal performance, they may come with increased energy consumption and maintenance costs. Taking these factors into account, we have chosen to design the system using medium filters to meet IAQ standards in Korea.

We also focused on supplying air uniformly in all spaces of the target facility, and in order to solve the obstacles (pressure, energy, etc.), we retrofitted the ventilation system to suggest optimal ventilation based on scientific evidence.

3.3 Final IAQ assessment

Currently, there are more than 125 underground shopping malls in Seoul, Korea; however, very few studies have been conducted that focus on improving the IAQ of these shopping malls. Therefore, in the present study, we investigated as well as improved the IAQ of the Gangnam underground shopping mall, which has the largest number of users in Korea.

Three representative locations were selected inside the Gangnam underground shopping mall to measure the improvement in the IAQ. Information regarding the outdoor air quality was collected from the Korean Meteorological Administration (Air Korea), which is located near the Gangnam underground shopping district.

In June 2019, retrofitting of the ventilation system was completed at the Gangnam underground shopping mall, including replacement of the supply/exhaust fans and installation of booster fans. Table 6 shows the changes in the indoor and outdoor temperature, humidity, and concentration of major pollutants in June 2020, that is, after the ventilation system was retrofitted.

We measured the IAQ of the Gangnam underground shopping mall in June because this month recorded the largest number of visitors due to the hot weather. The indoor temperature and relative humidity were measured to be approximately 24 °C and 54%, respectively. In zone A, where all the restaurants are concentrated, the average concentrations of $PM_{2.5}$ and CO_2 were measured be 46 μg m^{-3} and 574 ppm, respectively; note that the maximum value of CO_2 exceeded the recommended standard in this zone. In zone B, which is the central passageway of the shopping mall, the concentration of $PM_{2.5}$ was relatively low but that of CO_2 was higher. In zone C, which is the subway connection point, the concentration of $PM_{2.5}$ was the highest; this is probably due to the excess $PM_{2.5}$ being brought in by the subways.

Overall, we found that the average concentrations of the major pollutants met the standard criteria in June 2020. However, for several measurements, the concentrations of certain pollutants exceeded the corresponding recommended values in all three zones of the shopping mall. For example, in zone A, the excess ratios of $PM_{2.5}$ and CO_2 were approximately 2 and 5%, respectively; in zone B, the excess ratios of $PM_{2.5}$ and CO_2 were approximately 0.5 and 10%, respectively; and in zone C, the excess ratios of $PM_{2.5}$ and CO_2 were approximately 7 and 8%, respectively. The ventilation performance improved significantly in all three zones following the retrofitting; However, Zone C exhibited a relatively higher excess ratios of major pollutants compared to the other zones. This is likely due to Zone C being connected to the subway, resulting in a significant impact from pollutants generated during subway operations. The verified

Table 6 Indoor air contaminants and exceeding standard of the Gangnam underground shopping mall (June 2020)

Indoor air contaminants								
	Indoor air quality factors (Zone A: Restaurant area)							
	Temp. (℃)	**Humidity (%)**	**$PM_{1.0}$ (μg m^{-3})**	**$PM_{2.5}$ (μg m^{-3})**	**PM_{10} (μg m^{-3})**	**TVOC (μg m^{-3})**	**CO_2 (ppm)**	**Rn (Bq m^{-3})**
mean	24.2	55	12	15	37	177	574	0.5
std	1.1	7	9	12	23	39	203	0.3
min	20.0	34	1	0	2	125	384	0.0
max	27.0	71	83	83	167	868	1758	2.5
	Indoor air quality factors (Zone B: Central Passageway)							
	Temp. (℃)	**Humidity (%)**	**$PM_{1.0}$ (μg m^{-3})**	**$PM_{2.5}$ (μg m^{-3})**	**PM_{10} (μg m^{-3})**	**TVOC (μg m^{-3})**	**CO_2 (ppm)**	**Rn (Bq m^{-3})**
mean	23.4	53	7	9	25	158	654	0.7
std	0.7	6	7	8	17	32	308	0.4
min	20.0	37	0	1	1	125	385	0.0
max	25.0	70	60	81	147	535	2244	3.0
	Indoor air quality factors (Zone C: Subway connection point)							
	Temp. (℃)	**Humidity (%)**	**$PM_{1.0}$ (μg m^{-3})**	**$PM_{2.5}$ (μg m^{-3})**	**PM_{10} (μg m^{-3})**	**TVOC (μg m^{-3})**	**CO_2 (ppm)**	**Rn (Bq m^{-3})**
mean	24.2	55	32	35	50	198	609	0.6
std	0.9	6	8	9	17	45	261	0.3
min	22.0	36	10	2	15	125	382	0.0
max	27.0	73	83	83	167	650	2194	2.2

Excess rate of major pollutants over the corresponding standard criteria

Zone	**Contaminant**	**Total number of data points**	**Number of excess data points**	**Excess ratio (%)**
A	$PM_{2.5}$	4010	81	2.02
	PM_{10}	4010	96	2.39
	TVOC	4010	3	0.07
	CO_2	4010	204	5.09
	Rn	4010	0	0.00
B	$PM_{2.5}$	4010	20	0.50
	PM_{10}	4010	19	0.47
	TVOC	4010	2	0.05
	CO_2	4010	410	10.22
	Rn	4010	0	0.00
C	$PM_{2.5}$	4010	281	7.01
	PM_{10}	4010	46	1.15
	TVOC	4010	2	0.05
	CO_2	4010	309	7.71
	Rn	4010	0	0.00

underground shopping mall is a large facility divided into three areas: Area 1 (shopping centers), Area 2 (subway-connected), and Area 3 (floral district). As improvement measures for Zone C, there is ample potential for enhancement through the installation of small air purifiers, among other small-scale air purification devices, or the installation of shutters to block $PM_{2.5}$ inflow.

Although the concentrations of some of the pollutants exceeded the corresponding standard values under the retrofitted ventilation system, they were still significantly better than the concentrations measured in presence of the original ventilation system.

The ventilation system was retrofitted to improve the overall IAQ and booster fans were installed to supply air uniformly to all areas of the underground shopping mall. Concentrations of the pollutants CO_2, TVOC, and Rn improved by 33, 74, and 98%, respectively, whereas $PM_{2.5}$ concentrations remained approximately the same, as shown in Fig. 4. The concentration values of pollutants are shown in Table 6. In particular, CO_2 is a colorless and odorless gas that is generally used as a major indicator of indoor air pollution, and when the threshold is exceeded, it causes headaches, decreased respiratory function, and breathing difficulties. We have confirmed

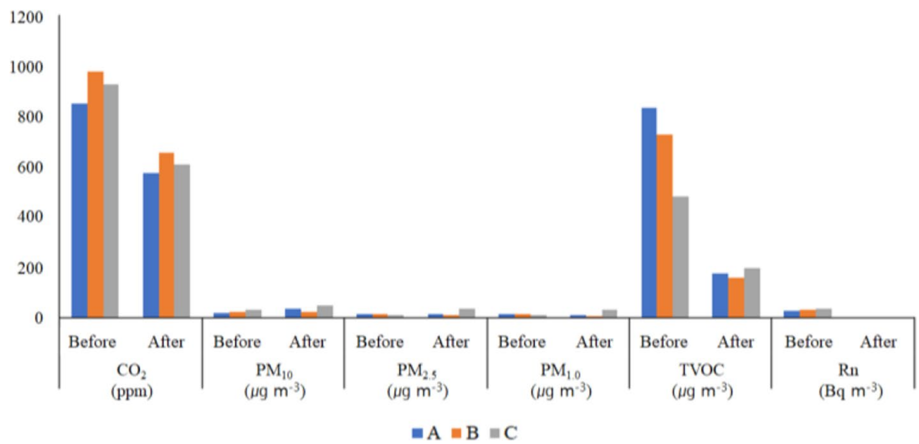


Fig. 4 Comparison of major pollutants concentration

the effect of improving IAQ by improving CO_2 by 33%, and have laid the foundation for improving health problems in indoor spaces through the retrofit of the ventilation system in underground shopping malls. Although the average concentrations of $PM_{2.5}$ are somewhat higher in the improved ventilation system, we believe that there is an overall improvement because of the decrease in the number of times the $PM_{2.5}$ concentrations are recorded to exceed the standard values; moreover, the retrofit ventilation system and booster fans facilitated uniform ventilation and reduced the total energy consumption. Figure 5 shows the change in the IAQ as measured in June 2020 following the installation of the retrofit ventilation system.

Comparison between the outdoor air concentration and indoor air concentration during the measured period based on $PM_{2.5}$ showed a similar trend, but a concentration tendency of the indoor $PM_{2.5}$ in Zone A and Zone C was higher than that of the outdoor $PM_{2.5}$. This represents that the concentration of air pollutants from indoor or outdoor sources through connected subway passages is significant. In IAQ research, the effect of outdoor air quality should be fully considered. However, in the case of this study, the effect was relatively less significant because the target underground shopping mall was connected to the subway. The primary cause of poor IAQ in subway systems is known to be larger particles, such as PM_{10}, which can be generated from mechanical friction (e.g., between trains and tracks, braking systems, and wear of electrical wires). Some of the generated PM_{10} particles settle in the tunnels, but they can become airborne due to air turbulence (i.e., piston effect) when a train passes through. As a result, PM_{10} concentrations in the train compartments can surge when the doors are opened [38]. This characteristic of the subway system explains the higher PM_{10} levels observed in Zone C.

As a result of reviewing the paper related to underground shopping malls, it was confirmed that research was conducted on indoor pollutants in aboveground shopping malls, but there was no research on indoor pollutants in underground shopping malls as in this paper. In the case of ground shopping malls, the concentration of TVOC, HCHO, and CO is a problem due to the nature of shopping malls [26] and some say that PMV (Predicted Mean Vote) greatly affects the satisfaction of the indoor environment [39], and an appropriate ventilation strategies in shopping malls. Shopping malls located underground have a greater risk than the ground, and a slightly more active ventilation strategy is needed than the ground.

Proposing IAQ problems for underground shopping malls is mainly underway in Asia, but there are very few cases of comprehensive improvement of several pollutants. The results of this study provided scientific evidence for research on improving IAQ using ventilation systems for special spaces called underground shopping malls, and suggested directions for improving IAQ in underground shopping malls around the world.

4 Conclusions

In this study, the evaluation of indoor air quality in a typical underground shopping mall in South Korea involved the modification of its indoor environment using retrofit ventilation facilities and monitoring factors contributing to indoor air pollution. Indoor air quality sensors capable of long-term monitoring were strategically installed throughout the underground shopping mall, and major indoor air pollutants were continuously monitored. The Gangnam underground shopping mall, one of the busiest malls in Korea, was selected for our study.

Findings are summarized as follows. First, a survey and detailed measurements on the indoor air quality of

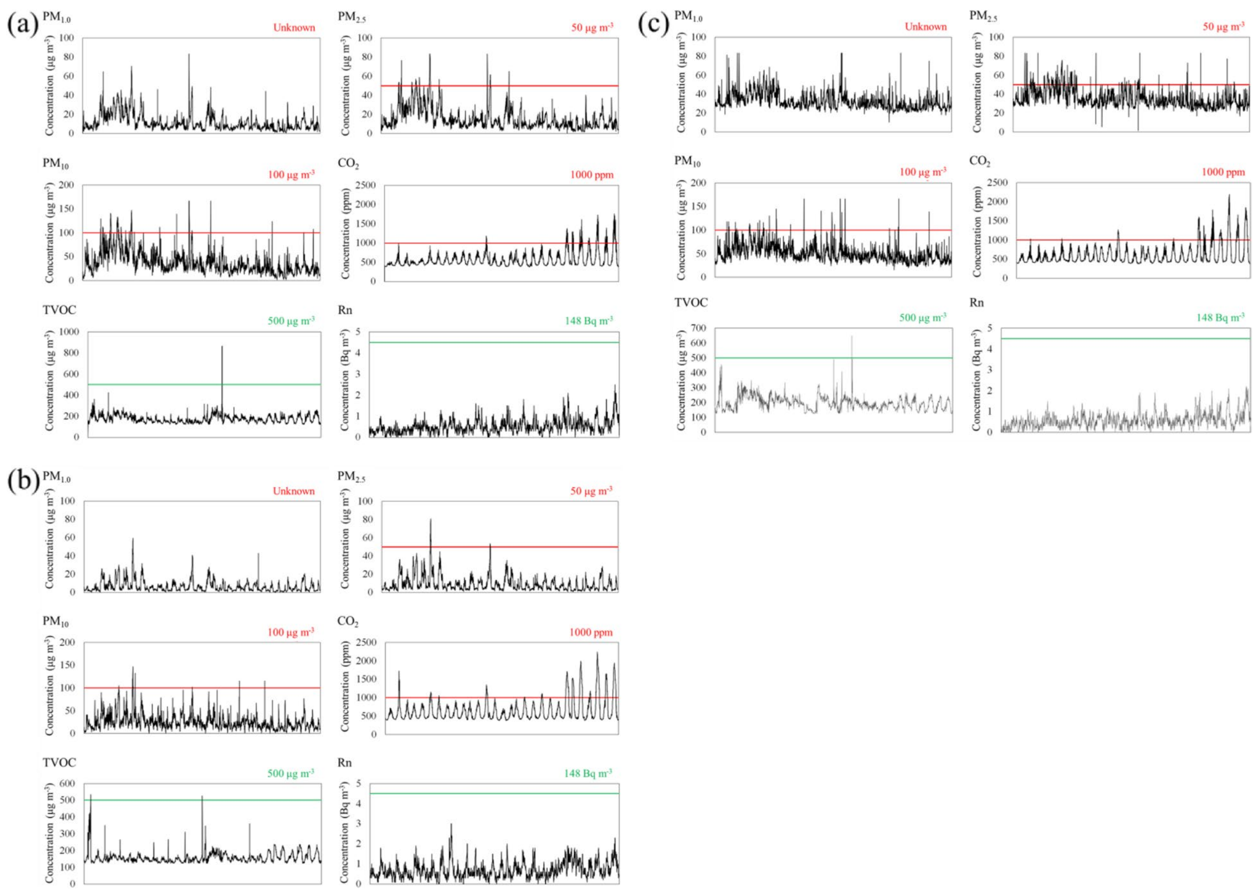


Fig. 5 Change in indoor air quality due to retrofit ventilation system as measured in June 2020 (red lines: maintenance criteria; green lines: recommendation criteria; **a** Zone A (Restaurant area); **b** Zone B (Central passageway); **c** Zone C (Subway area))

the shopping mall in the presence of the original ventilation system were conducted. Consequently, the need to improve the ventilation system was confirmed by customers and internal affiliates of the shopping mall. Next, the main ventilation system of the underground shopping mall was retrofitted with fans of improved performance (air volume: 45,000 m^3 h^{-1}, positive pressure: 16 kPa, FEG: 80, and power: 26 kW). Additionally, booster fans were installed in various locations to ensure uniform air supply throughout the shopping mall. This retrofitting enabled the ventilation system to operate flexibly, maintaining the same air volume in all areas of the shopping mall. Owing to the improved ventilation system, concentrations of CO_2, TVOC, and Rn decreased by 33, 74, and 98%, respectively. Although $PM_{2.5}$ concentrations remained approximately the same, proper indoor air quality was still maintained owing to the reduced energy consumption facilitated by the flexible operation of the retrofitted ventilation system. The results of the present study are expected to be useful for solving important national problems, as they can be applied to several multi-use facilities (e.g., day care centers, elderly care facilities, and other underground shopping malls).

In conclusion, modifying ventilation systems in underground shopping malls so that high-efficiency fans and even air volume can appear in the entire area is likely to increase the satisfaction of customers by maintaining the desired indoor air quality. However, the local government and facility managers should continue to participate in monitoring and managing the indoor air quality of underground facilities for long-term sustenance. The overall summary of this study is presented in Supplementary Material. The results of the study can be used by facility managers and policymakers to improve the indoor air quality of underground shopping districts and formulate revised plans for future guidance. Improving the indoor air quality of underground facilities that are used by many citizens is expected to create an overall safer and healthier environment for everyone.

Authors' contributions

Kichul Kim: Writing - Original Draft, Visualization. Jiwoong Kim: Methodology & Investigation. Yun Gyu Lee: Project administration. Seunghwan Wi: Writing - review & editing, Conceptualization. Sumin Kim: Conceptualization, Supervision.

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Availability of data and materials

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Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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