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Research Article

Indoor Pollutant Reduction Performance of Different Mechanical Ventilation Filters in Apartment Buildings

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High-efficiency particulate air (HEPA) and charcoal filters have been applied to ventilation systems to save energy and reduce pollutants. However, such filters only work for specific types of pollutants, and their performance is not always sustainable. This study compares the pollutant reduction performance of TiO_2 photocatalytic filters with HEPA and charcoal filters in mock-up experiments with toluene as the pollutant, changing air volume, and varying ventilation frequencies. The results show that the HEPA filter was ineffective at reducing toluene, and the charcoal filter was found to have the fastest reduction rate until 180 min after the start of the experiment. However, after 180 min when the charcoal filter was saturated, its pollutant reduction performance rapidly declined, resulting in low persistence. Conversely, the TiO_2 photocatalytic filter had a lower reduction rate than that of the charcoal filter but had a continuous pollutant reduction performance during 720 min. Comparing the pollutant reduction effect of the TiO_2 photocatalyst filter and the charcoal filter with a reduced amount based on the experimental time, the TiO_2 photocatalyst filter has a maximum pollutant reduction effect of about seven times and at least about two times. This study confirms that HEPA and charcoal filters reduce gas pollutants, and it was found that combining TiO_2 photocatalysts with ventilation devices can improve indoor air quality in apartment buildings.

1. Introduction

Reducing energy consumption is a widely recognized strategy to decrease carbon emissions and combat global warming, particularly in the context of building energy efficiency. Buildings are often constructed with airtight features to minimize air leakage and save energy. However, this can result in reduced indoor and outdoor air circulation, leading to poor ventilation and difficulties in removing pollutants from indoor and outdoor sources. Consequently, such pollutants can have adverse effects on the health of indoor occupants. Pollutants are typically categorized into particulate and gaseous pollutants based on their phase.

Particulate pollutants, such as PM10 and PM2.5, are representative indoor pollutants, while gaseous pollutants, such as volatile organic compounds (VOCs), NO_x, and SO_x, are commonly found both indoors and outdoors [1, 2]. These pollutants are considered key substances that need to be effectively managed, and their indoor/outdoor criteria are outlined in the indoor air quality guidelines provided by the World Health Organization (WHO) [3].

To address the problem of poor ventilation and promote indoor/outdoor air circulation, the Ministry of Land, Infrastructure, and Transport of Korea has mandated implementing mechanical ventilation systems in buildings through Article 11 of the Regulations for Building Facilities [4]. Mechanical ventilation systems enable indoor ventilation by introducing outdoor air, even in situations where natural ventilation is challenging. This can improve the effectiveness of pollutant removal by inducing airflow in designated areas or spaces.

Currently, mechanical ventilation systems in apartment buildings typically utilize dust collection and activated carbon filters to remove pollutants. Such filters are subject to KS B 6141 standards, which specify various requirements, such as the particle collection rate, ventilation resistance, and amount of dust collected [5]. However, there is a growing need for more effective and sustainable solutions that can address the challenges associated with indoor air pollution and ventilation in buildings.

1.1. Literature Review on Dust Collection Filters. Several studies have investigated the effectiveness of dust collection filters in removing indoor pollutants. For instance, Day et al. [6] investigated the exposure of volunteers to PM2.5 and ozone using a combination of dust collection filters and electrostatic precipitator filters. Xu et al. [7] evaluated ventilation and air purification systems equipped with high efficiency particulate air (HEPA) filters as dust collection filters and found that they can reduce particulate matter (PM), carbon monoxide, and carbon dioxide, thus alleviating asthma symptoms in patients. Singer et al. [8] installed minimum efficiency reporting value (MERV) 13–16 filters in cooling systems to assess their effectiveness in reducing PM2.5 emitted from sources, such as California highways and home cooking, and reported a remarkable reduction of 93–98%.

Souzandeh et al. [9] developed a nanofilter that exhibited promising results in removing particulate and gaseous pollutants. Kim and Lee [10] and Brown et al. [11] confirmed the efficiency of various filters in removing PM and allergens. Specifically, HEPA filters have been shown to have a particulate pollutant removal efficiency of over 99% when compared to that of conventional medium filters [12–15].

However, one limitation of dust collection filters, including HEPA filters, is the accumulation of pollutants over time, leading to increased airflow resistance and potential degradation in filter performance, including airflow velocity and power consumption [16]. To address this problem, researchers have proposed installing prefilters in conjunction with HEPA filters to enhance efficiency and extend service life [17]. Currently, prefilters are commonly used in ventilation systems in apartment buildings in combination with dust collection filters, such as HEPA filters, to optimize their performance.

Numerous studies have confirmed the effectiveness of dust collection filters, such as HEPA filters, in removing particulate pollutants, although their efficiency may decrease over time. However, it has been established that dust collection filters are less effective in removing gaseous pollutants [18, 19].

1.2. Literature Review on Charcoal Filters. To improve the effectiveness of dust collection filters, a proposed approach involves combining an adsorption filter with a dust collection filter to adsorb and remove gaseous pollutants [20, 21]. Studies have demonstrated that a combination of charcoal and dust collection filters can reduce VOCs inside an aircraft by 30% [22]. Additionally, computational fluid dynamics (CFD) modeling has been employed to derive an adsorption model for activated carbon fibers with an acetaldehyde reduction effect, aiming to utilize the adsorption performance of activated carbon [23].

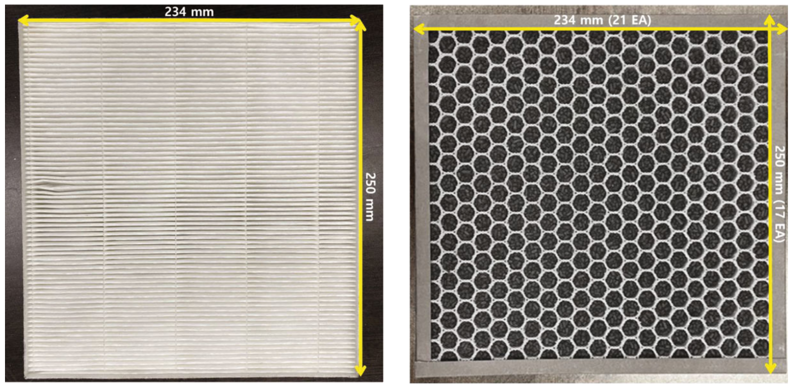
Gallego et al. [24] confirmed that commercially available activated carbon filters in air purifiers can reduce several VOCs, including alcohol and ether. Maximoff et al. [25] investigated the capacity of activated carbon filters in adsorbing VOCs and toxic gases generated during fires. Ligotski et al. [26] estimated the service life of activated carbon filters by measuring the time taken to reduce the concentration of toluene to 0.09 ppm. Moreover, several studies have explored the use of dust collection and activated carbon filters in ventilation systems. However, similar to dust collection filters, activated carbon filters also require regular replacement and management owing to their limited service life [20, 21, 27, 28]. Furthermore, there is a potential concern that adsorbed pollutants can be released and reintroduced into indoor spaces due to differences in pollutant concentrations, highlighting the urgent need for solutions to address this problem.

1.3. Literature Review on TiO_2 Photocatalysts. In addition to activated carbon filters, TiO_2 photocatalysts are used for removing gaseous pollutants. TiO_2 photocatalysts generate highly oxidizing radicals via photochemical reactions with UV rays [29–38]. The radicals can decompose or adsorb gaseous pollutants, leading to their removal through oxidation reactions, without generating additional pollutants as some other photocatalysts do. Several studies have been conducted to investigate the performance of TiO_2 photocatalysts in reducing gaseous pollutants, as well as in decomposing and adsorbing different substances, such as NO_x and SO_x, which are outdoor air pollutants that contribute to the formation of PM [39–41].

Cassar et al. [42] installed concrete exterior materials mixed with TiO_2 photocatalysts in the Jubilee Church in Rome and observed a reduction of 30–40% in NO_x. Luna et al. [43] coated the surface of stone finishing materials with TiO_2 photocatalysts and confirmed their effectiveness in smoke removal. Lettieri et al. [44] applied a TiO_2 photocatalytic coating to stone surfaces and found that the NO_x reduction effect lasted for eight months. Ramakrishnan and Orlov [45] added TiO_2 photocatalysts into concrete and reported an increase in NO_2 adsorption performance compared to that of conventional concrete. Furthermore, it has been demonstrated that TiO_2 photocatalysts added to asphalt pavement and mortar can reduce NO_x by 60–80% [45].

Several studies have confirmed the efficacy of TiO_2 photocatalysts in removing gaseous pollutants. For instance, a numerical analysis confirmed the reduction of pollutants using photocatalysts attached to a reaction device [46]. Montecchio et al. [47] utilized a CFD simulation to demonstrate the effectiveness of a reaction device in reducing VOCs as gaseous pollutants. Zhang et al. [48] applied doped photocatalysts to glass windows in actual buildings and confirmed the reduction of formaldehyde during natural ventilation. Although several studies have focused on reducing indoor pollutants using TiO_2 photocatalysts, there is a general lack of research that combines TiO_2 photocatalysts with ventilation systems to compare their effectiveness with existing pollutant reduction methods.

To address this gap in the literature, this study installed HEPA and charcoal filters in addition to TiO_2 photocatalysts



(a) (b)

Figure 1: Filter types. (a) HEPA and (b) charcoal.

Table 1: Filter dimensions and features.

Filter type	Dimensions (width × length × thickness)	Rating	Number of airflow paths	Purpose
HEPA	234 mm × 250 mm × 20 mm	H13	—	Dust collection
Charcoal	234 mm × 250 mm × 10 mm	—	357 ea.	Gas adsorption

in ventilation systems similar to those used in existing apartment buildings. The pollutant reduction performance of each filter were compared at varying air volumes and ventilation frequencies to evaluate their effectiveness in removing commonly found gaseous pollutants in apartment buildings. Specifically, a TiO_2 photocatalyst coating agent was applied to the TiO_2 photocatalytic filter designed and developed by Song et al. [49] to remove NO_x using ducts. Toluene was used a representative indoor gas pollutant in the experiment as suggested by the WHO [50], ASHRAE [51], and Ministry of Environment of the Republic of Korea [52]. The experiment was conducted for each filter type, where the number of ventilations per hour and the air volumes were changed. To our knowledge, the approach of this study has not been previously used. The results of this study show that indoor pollutants in apartments can be removed by applying this method in areas with poor air environments due to high external pollutant concentrations and suggests a way to improve the indoor air environment. In addition, the study results can be used as a reference for the development of ventilation devices to improve the indoor air environment in buildings other than apartment buildings.

2. Materials and Methods

2.1. Dust and Charcoal Filter. In this study, three types of filters were employed to effectively remove different types of pollutants. First, the highly efficient HEPA filter, renowned for its widespread use in dust collection owing to its remarkable particulate removal rate of 99.95%, was utilized. The HEPA filter in Figure 1(a) is rated as H13, based on the EN-1822 standard, making it one of the top-performing filters in the industry [53]. The second filter employed was the activated carbon filter in Figure 1(b), which is specifically designed for deodorization and adsorption of gaseous pollutants. Images of both filters are shown in Figure 1, and Table 1 lists the critical parameters for each filter, ensuring their effective performance.

Table 2: Charcoal filter weight measurements.

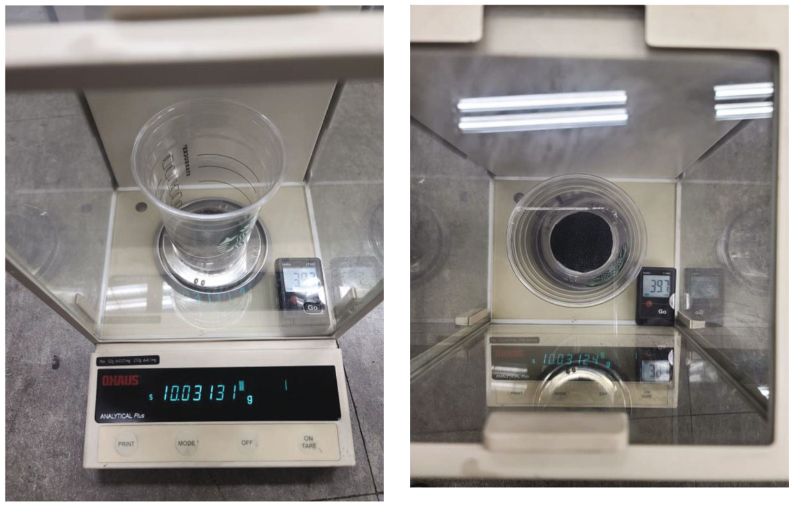
Contents	Counts	Weight
Charcoal filter airflow honeycomb	357	142.8 g
Selection honeycomb	25	10 g
Charcoal filter weight	1	0.4 g

As indicated in Table 2 and Figure 2, the charcoal filter contains 357 airflow paths in the honeycomb structure, and the measured weight of the activated carbon in Figure 2(a) was 142.8 g.

The weight was estimated based on the weight of the activated carbon applied to 25 airflow paths, which were randomly selected out of the 357 available paths. During the weight measurement, the humidity inside the electronic scale in Figure 2(b) was 39.7%.

2.2. TiO_2 Photocatalytic Filter. A tubular filter containing a TiO_2 photocatalyst, which was designed and developed in previous experiments, was used as the third type of filter. The filter has a unique structure, as depicted in Figures 3 and 4, with a coating agent mixed with a TiO_2 photocatalyst applied internally, and the capability to accommodate UV lamps for photocatalytic reactions.

In the experiment, the HEPA, charcoal, and TiO_2 photocatalytic filters were installed in a ventilation system that is commonly used in apartment buildings, and the reduction performance of toluene was compared for each filter at varying ventilation frequencies.



(a) (b)

Figure 2: Charcoal filter measurements. (a) Weight and (b) humidity.

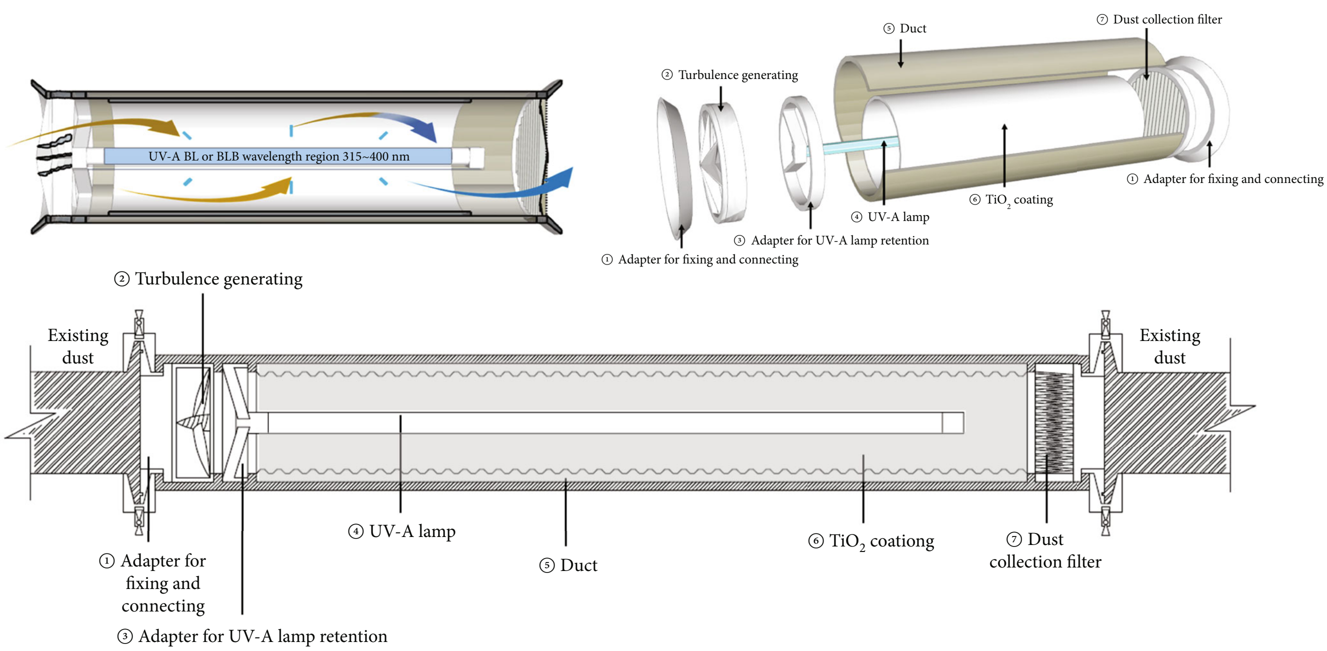
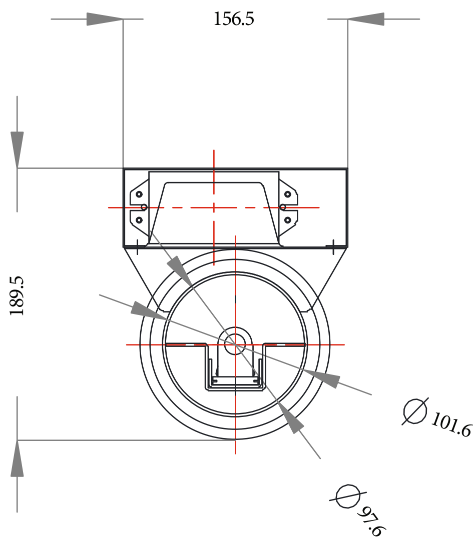


Figure 3: Concept of the TiO_2 photocatalytic filter.

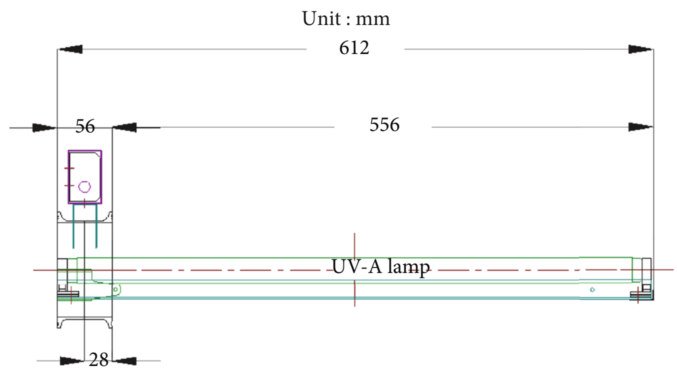
2.3. Overview of Ventilation System. The filters were combined with a designed and fabricated reaction device and the existing ventilation system, as shown in Figure 5. The ventilation system with charcoal filter applied is shown in Figure 5(a), the HEPA filter application is shown in Figure 5(b), and the ventilation system with TiO_2 photocatalyst filter is configured as shown in Figure 5(c).

The reaction device and filter were installed in the supply air (SA) section of the ventilation system, which provides air to the indoor space. This setup facilitates the removal of gaseous pollutants that may enter from the outside through internal circulation, even in scenarios where ventilation is challenging because of high external pollutant concentrations.

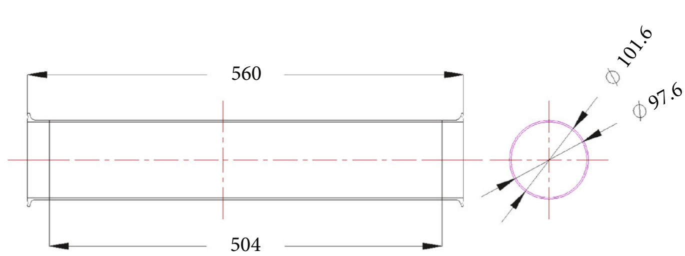
2.4. Mock-Up Experiment. A mock-up experiment was developed to assess the toluene reduction performance of the ventilation system, incorporating HEPA and charcoal filters designed to reduce particulate and gaseous pollutants, as well as the specially designed and fabricated TiO_2 photocatalytic filter. Since there is no established method for evaluating the performance of ventilation systems equipped with photocatalysts, certain elements of the indoor air purifier test method (SPS-KACA002-132) of the Korea Air Cleaning Association [54] were applied to the shape and internal configuration of the mock-up. Table 3 presents a comparison between the conditions of the photocatalytic ventilation system (mock-up) designed in this study and indoor air purifier method.



(a) Ultraviolet lamp power supply



(b) Ultraviolet lamp holder



(c) Reactor unit front and section

(d) Photographs of the reactor

FIGURE 4: TiO_2 photocatalytic filter design drawing and production photographs.

The existing test method for evaluating air purifier pollutant purification typically uses a concentration criterion of 10.00 ppm [54] and employs an accelerated test that involves exposing the air purifier to high-concentration pollutants for 30 min to assess its purification efficiency. However, in this study, a lower pollutant concentration of 1.00 ppm was utilized, which is 1/10 of the concentration used in the existing test method. By using this concentration, the data with errors that may occur between experiments at concentrations of 0.02 ppm, the resolution of the measuring

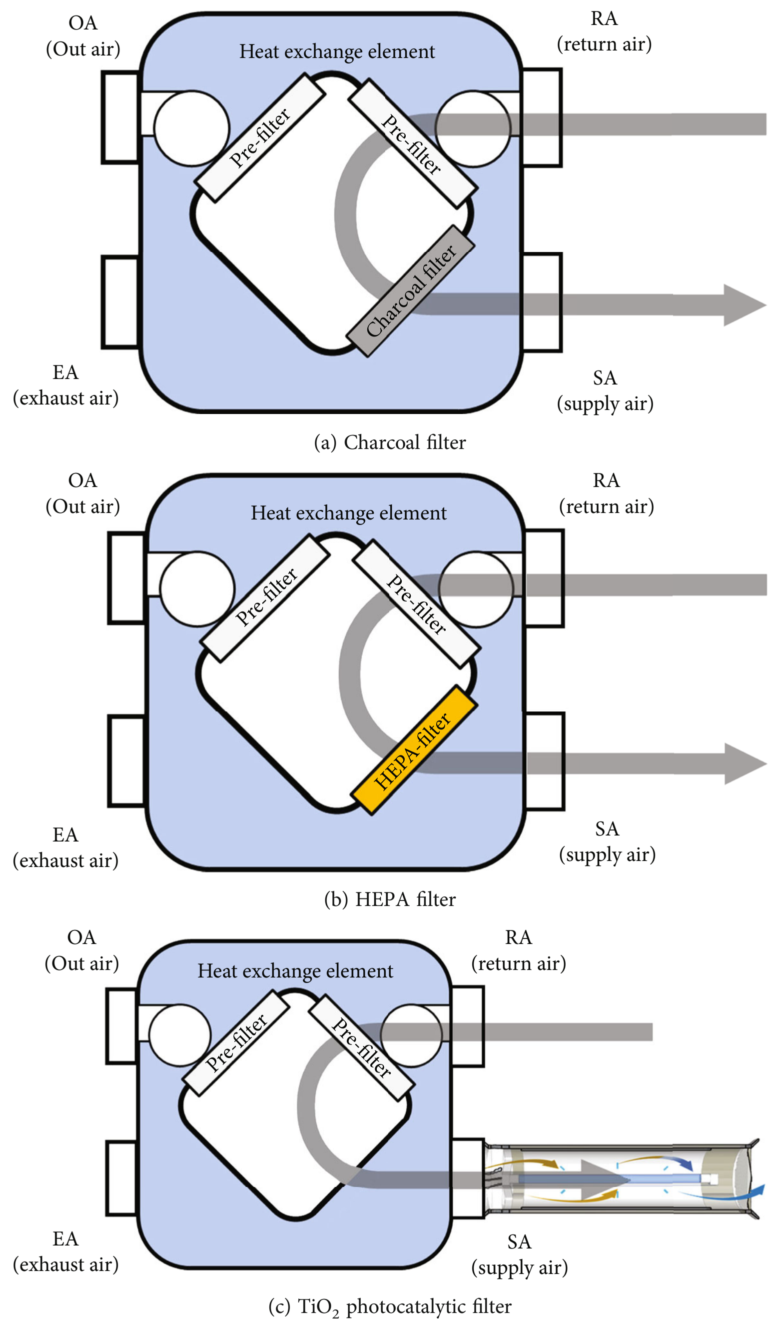


Figure 5: Conceptual diagram of ventilation system application for each filter type.

equipment used in this experiment, can be reduced. Additionally, a concentration of 1.00 ppm is sufficient to confirm the effectiveness of TiO_2 photocatalysts as suggested by ISO 22197-3:2019 [55], an international standard for reducing pollutants of TiO_2 photocatalysts. Furthermore, the existing test method does not include any condition related to the photocatalytic activity. Hence, a UV-A lamp, as used in previous studies, was employed in this study. Accordingly, a Philips TL-D 18 W BL lamp with a maximum light intensity of 20 W/m^2 was used in this study. By applying irradiance, the oxidation reaction of the TiO_2 photocatalyst is promoted according to the increase in UV-A irradiance, confirmed by Song et al. [49], resulting in an improvement in the overall pollutant reduction rate.

A polycarbonate material was used to prevent the generation of pollutants other than the gas used in the experiment, as well as adsorption and chemical reactions. Additionally, a mixing fan was installed on the ceiling to facilitate active dilution of the internal air. The mock-up design drawing and a photograph of the installed mock-up are shown in Figure 6.

As illustrated in Figure 7, the installed mock-up comprised connections on the right side for the ventilation system, with a pollutant inlet in the upper left corner and an

Table 3: Comparison of the mock-up and indoor air purifier experimental methods.

Conditions	Evaluation criteria Indoor air purifier method (SPS-KACA002-132) [54]	Photocatalytic ventilation system
Temperature	$23 \pm 3^{\circ}C$	$23 \pm 3^{\circ}C$
Humidity	$50 \pm 10\%$	$50 \pm 10\%$
Experimental gas concentration	10 ± 1 ppm	1 ± 0.1 ppm
UV-A irradiance	None	$20\ W/m^2$
Test chamber size	$8.0 \pm 0.5\ m^3$, $30.0 \pm 1.5\ m^3$, $50.0 \pm 1.5\ m^3$	$0.65\ m \times 1.15\ m \times 1.75\ m$ ($1.31\ m^3$)
Target pollutants	NH_3, CH_3COOH, CH_3CHO, C_7H_8, HCHO	C_7H_8

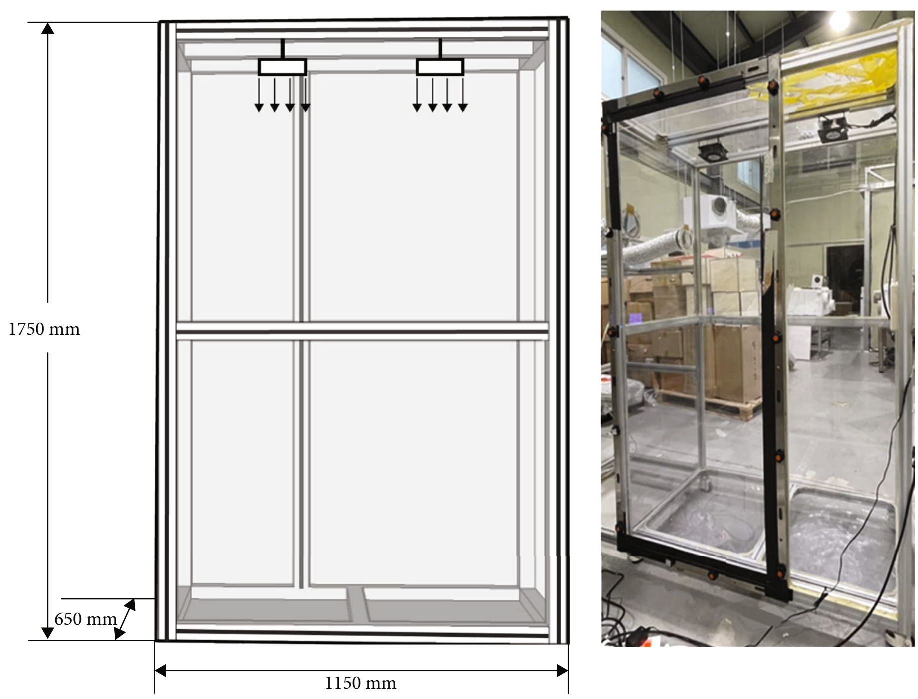


Figure 6: Mock-up design drawing and photograph.

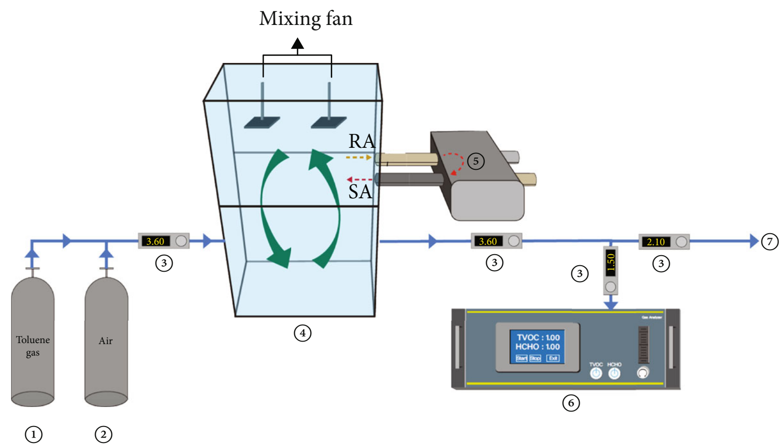
outlet connected to the measurement equipment in the lower left corner. The ventilation system used in the mock-up had an air volume of $140\ m^3/h$, which corresponds to the typical ventilation rate for an $84\ m^2$ apartment. The experimental setup incorporating the ventilation system and mock-up is depicted in Figure 7.

2.5. Measurement Equipment. In the mock-up experiment, a photoionization detector (PID) sensor capable of measuring the concentration of toluene (pollutant used in the experiment) was used as the measuring instrument. Furthermore, the PID sensor can also measure the byproducts generated, such as benzene (C_6H_6) and butadiene (C_4H_6), when toluene (C_7H_8) is decomposed according to the chemical reaction of the photocatalyst.

Additionally, a SLIDE-AC was utilized to maximize the light intensity of the UV-A lamp installed in the tubular photocatalytic filter, and a thermohygrometer was employed to measure the internal temperature and humidity. Further details regarding the measurement equipment are presented in Table 4.

2.6. Experimental Conditions. The objective of the experiment was to assess the pollutant reduction efficacy of each filter, including the specially designed and fabricated TiO_2 photocatalytic filter, applied in the ventilation system. The experiment involved varying the air volumes to achieve one and five air exchanges per hour within the mock-up volume to investigate the pollutant reduction performance. Moreover, a higher concentration of pollutants than the standard concentration in actual environments was employed to evaluate the sustained effect of each filter. To ensure consistency, the experiment was conducted in triplicate for each ventilation frequency. At the conclusion of each experiment, the mock-up was opened to discharge residual pollutants, and the internal temperature and humidity were maintained at $25 \pm 2.5^{\circ}C$ and $50 \pm 10\%$, respectively.

The ventilation frequency was determined by measuring the wind speed of the air moving in the circular duct, utilizing the duct air volume measurement method outlined in the Society of Air-Conditioning and Refrigerating Engineers of Korea (SAREK Standard 201-2013) [56]. The



① Toluene gas
② Air gas
③ Digital flow meter
④ Mock-up chamber
⑤ Photocatalytic filter
⑥ Measurement equipment
⑦ By-pass

FIGURE 7: Conceptual schematic of the mock-up experiment.

TABLE 4: Overview of experimental measurement equipment used in the mock-up.

Equipment name	Airwell plus gas analyzer				
Measuring gas	Toluene				
Sensor type	PID				
Range	0–10 ppm				
Resolution	0.02 ppm				
Max. concentration	100 ppm				
Min. concentration	0.1 ppm				
Flow rate	1.5 L/min				
Equipment name	DLC-0.5 K 220/240		Testo 174H		
Capacity	0.5 KVA		Temperature range	-20 to +70°C	
Input/output	220 V/5-240 V				
Current	2 A		Humidity range	0%–100% RH	

fundamental conditions of the mock-up experiment and the wind speed measurement method are presented in Tables 5–7.

The experiment utilizing the calculated wind speed was conducted in four sequential steps. First, toluene gas, a representative indoor gaseous pollutant, was continuously injected into the mock-up at a concentration of 1 ppm and a flow rate of 3.6 L/min until the experiment was concluded. Additionally, a flow rate of 3.6 L/min, equivalent to the injection flow rate, was discharged and routed to the measurement equipment and bypass to maintain the pressure within the mock-up.

Second, following the injection of toluene gas into the mock-up, the airtightness of the mock-up was confirmed, and a uniform internal concentration distribution of 1 ppm was verified and maintained.

Third, on confirming the maintenance of the concentration, each of the HEPA dust collection, activated carbon, and photocatalytic filters was connected, and the reduction in toluene concentration was determined. Furthermore, the time required to reach the minimum concentration was measured to assess the efficiency of the filters.

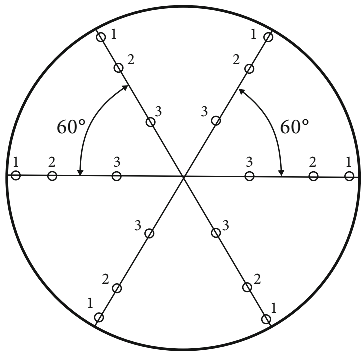
Fourth, upon achieving convergence to the minimum concentration, the time at which the activity of each filter ceased was investigated. The mock-up was then confirmed to be airtight once again by examining the increase in pollutant concentration inside the mock-up through the continuous injection of toluene gas.

The four steps were repeated for each ventilation frequency of 1 and 5 air changes per hour (ACH). Finally, the results of the experiment were used to compare the toluene reduction performance of each filter.

Table 5: Mock-up experimental conditions.

Mock-up dimensions (volume)	Content	Value	Content	Value
$0.65\,m \times 1.15\,m \times 1.75\,m$ ($1.31\,m^3$)	Temperature	$25 \pm 2.5^{\circ}C$	Test gas	C_7H_8
	Humidity	$50 \pm 10\%$	Gas concentration	1.00 ± 0.1 ppm
	UV-A Irradiance	$20\,W/m^2$	Experimental flow rate	3.6 L/min
	Number of tests	At least three per condition	ACH	1 ACH 5 ACH

Table 6: Calculation method of the ventilation duct air volume.



Number of measurement points for each diameter	Data point position (unit: mm)				
	Data point 1	Data point 2	Data point 3	Data point 4	Data point 5
6	0.032D	0.135D	0.321D	-	-
8	0.021D	0.117D	0.184D	0.345D	-
10	0.019D	0.077D	0.153D	0.217D	0.361D

Table 7: Wind speed calculation of TiO_2 photocatalytic reaction device by ACH in mock-up.

Content	Cross-sectional area and outlet wind speed
Outlet cross-sectional area	$0.00785\,m^2$
Wind speed 1 m/s hourly air volume	$28.26\,m^3/h$
Wind speed of 1 ACH	0.046 m/s
Wind speed of 5 ACH	0.23 m/s

3. Results and Discussion

3.1. Mock-Up Ventilation Frequency 1 ACH Result. As described above, the mock-up experiment to examine the toluene reduction performance was conducted for 1 ACH. The experiment followed the aforementioned four steps, and the results are presented in Figure 8 and Table 8.

Based on the experimental results, the tubular photocatalytic filter required 377 min to reach a minimum concentration of 0.6 ppm, and the maximum reduction effect was sustained for 403 min (720 min−317 min), after which the reaction ceased because the UV lamp was turned off (as discussed in Section 3.3). Subsequently, the toluene concentration started to rise again as the activity of the filter ceased.

For the activated carbon filter, it took 100 min to reach a minimum concentration of 0.55 ppm, and the maximum reduction effect was sustained for 24 min (124 min −100 min). Thereafter, the toluene concentration started increasing again, indicating that the charcoal filter was saturated, and its adsorption performance terminated 124 min after the start of the experiment. As for the HEPA filter, no pollutant reduction effect was observed.

3.2. Mock-Up Ventilation Frequency 5 ACH Result. A second experiment for 5 ACH was conducted to examine changes in the toluene reduction performance of each filter and the retention performance for each filter. The experiment was conducted in the same sequence as above, and the results are shown in Figure 9 and Table 9.

Under a ventilation rate of 5 ACH, the tubular photocatalytic filter achieved a minimum concentration of 0.58 ppm in 180 min, which is approximately 48% faster compared to that of the experiment conducted at 1 ACH. This indicates that toluene, which possesses high chemical molecular bonds, was effectively reduced through decomposition. Furthermore, the byproducts generated during toluene decomposition were also efficiently decomposed.

In contrast, the charcoal filter exhibited a lower reduction efficiency compared to the TiO_2 photocatalytic filter, and the concentration of toluene began increasing again after 100 min, similar to the results observed for 1 ACH. This suggests that the duration of pollutant reduction for the charcoal filter remains consistent regardless of the ventilation frequency. Notably, the HEPA filter did not exhibit any reduction effect even with increased ventilation frequency.

3.3. Total Mock-Up Ventilation Frequency Test Result. The toluene reduction performance of each filter was assessed based on the 1 and 5 ACH experiments described earlier. The amount of toluene removed was calculated and compared for the time period from 60 min after the start of the experiment when pollutant reduction began, up to 780 min

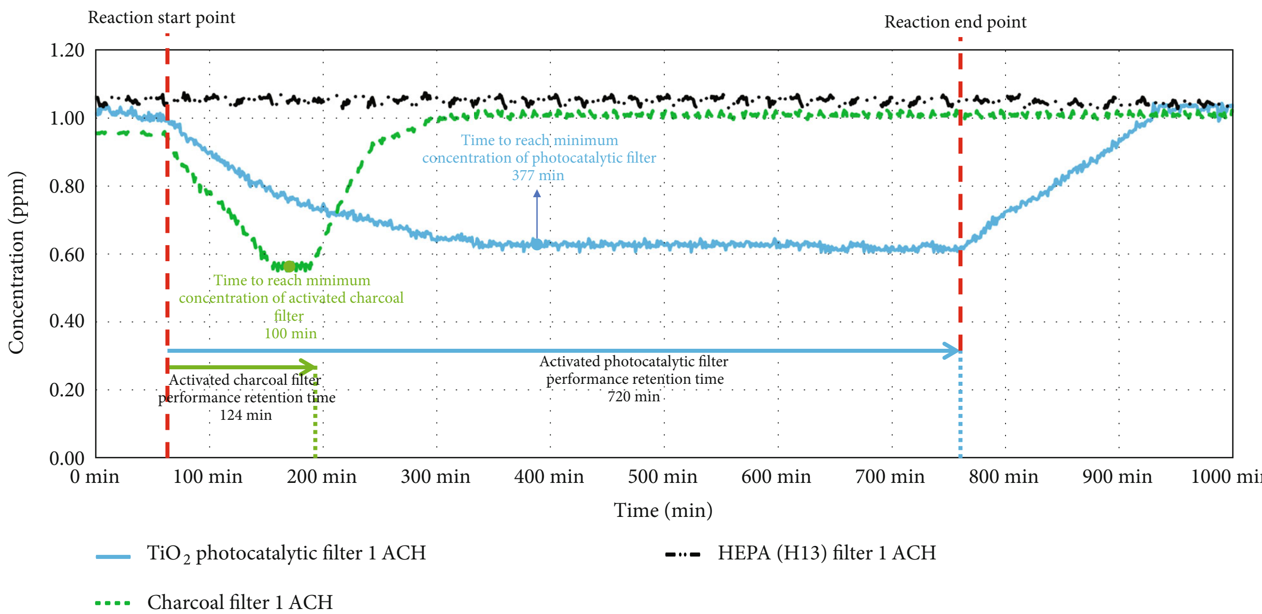


Figure 8: Toluene reduction for 1 ACH.

Table 8: Toluene reduction performance for 1 ACH.

Classification	Start concentration	Minimum concentration	Reduction rate	Duration of reduction effect
TiO_2 photocatalytic filter	1.00 ppm	0.60 ppm	40.00%	720 min
Charcoal filter	0.95 ppm	0.55 ppm	42.11%	124 min
HEPA filter	1.04 ppm	1.02 ppm	1.92%	0 min

when the activity of the photocatalytic filter was terminated by turning off the UV lamp.

The toluene removal amounts for each filter type were compared at 60 min intervals, using Equations (1) and (2), as specified in ISO 22197-3:2019 [55].

$$R = \frac{\varnothing_{T0} - \varnothing_T}{\varnothing_{T0}} \times 100, \tag{1}$$

$$\eta_t = R \times \frac{\varnothing_{T0} \times f \times 60}{100 \times 22.4}, \tag{2}$$

where R denotes the removal percentage of toluene (%), $\varnothing_{T0}$ indicates the supply volume fraction of toluene (μL/L), $\varnothing_T$ indicates the toluene volume fraction at the exit (μL/L), η_t corresponds to the quantity of toluene removed by the test piece (μmol), and f denotes the standardized test gas flow rate (3.6 L/min, 0°C, 101.3 kPa, dry gas).

Additionally, the reduction rates based on the surface areas of each filter were compared. Since a direct quantitative comparison of the HEPA, charcoal, and photocatalytic filters is not feasible owing to differences in the surface area, the removal amount per unit area in direct contact with air was calculated. The surface area of each filter is listed in Table 10.

The toluene reduction results for each filter type according to the removal amount and unit area calculation were divided into 60 min intervals to calculate the removal amount accumulated over 60 min. The corresponding results are shown in Figure 10 and Table 11.

The experimental results show that the charcoal filter demonstrated a high reduction performance for the first 180 min following the initiation of toluene reduction, with a maximum reduction rate of 4.09 μmol/cm^2·min. However, the toluene reduction ceased thereafter owing to the adsorption saturation of the filter, resulting in the release of toluene back into the chamber.

In contrast, the TiO_2 photocatalytic filter exhibited toluene reduction from the outset of the experiment, maintaining a reduction rate of 0.64 to 0.65 μmol/cm^2·min until 720 min, when the UV lamp was turned off. Conversely, the HEPA filter did not exhibit any significant toluene reduction effect.

Based on these findings, it was observed that the charcoal filter may inadvertently worsen the indoor air quality by rereleasing pollutants into the environment after saturation, unless continuous management is performed. In contrast, the TiO_2 photocatalytic filter demonstrated sustained pollutant reduction performance as long as the UV lamp remained switched on, despite its lower reduction performance per unit time compared to the charcoal filter. Furthermore, the TiO_2 photocatalytic filter achieved a consistent reduction level even with increased ventilation frequency, although the time required to reach the maximum reduction varied.

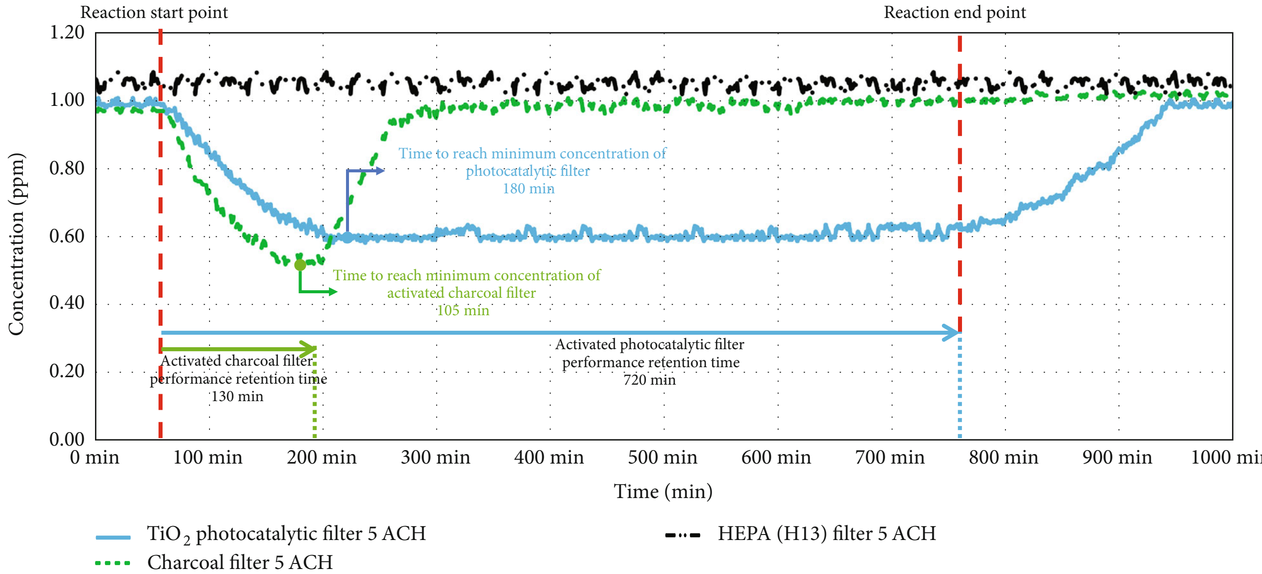


Figure 9: Toluene reduction for 5 ACH.

Table 9: Toluene reduction performance for 5 ACH.

Classification	Start concentration	Minimum concentration	Reduction rate	Duration of reduction effect
TiO_2 photocatalytic filter	0.99 ppm	0.58 ppm	41.41%	720 min
Charcoal filter	0.97 ppm	0.52 ppm	46.39%	130 min
HEPA filter	1.05 ppm	1.02 ppm	2.86%	0 min

Table 10: Surface areas for the different filter types.

Filter type	Surface area (cm^2)
HEPA	585
Charcoal	585
TiO_2 photocatalytic	1,544.58

Therefore, it is expected that similar reduction effects could be achieved at a ventilation frequency of 0.5 ACH, which is the standard ventilation rate for apartment buildings in Korea, although this falls outside the scope of this study.

3.4. Discussion. In this study, the effectiveness of different filters in reducing gaseous pollutants in indoor environments after installation in ventilation systems was compared and examined. The noteworthy implications of this study are discussed below.

First, existing ventilation systems typically utilize dust collection filters designed to remove particulate pollutants. In recent years, activated carbon filters, which are capable of removing gaseous pollutants, have been installed in conjunction with HEPA filters to enhance the pollutant removal performance. However, this method has limitations because the adsorption capacity of activated carbon can be exceeded, resulting in a reduced pollutant removal effectiveness. To overcome this limitation, one potential solution involves using TiO_2 photocatalysts.

Second, TiO_2 photocatalysts generate radicals with oxidizing properties through photochemical reactions utilizing the band gap energy of UV rays. However, it is challenging to introduce naturally occurring UV rays into indoor spaces because of external reflection and obstruction by windows and doors. Furthermore, the potential health risks associated with UV rays limit their use in indoor environments. Therefore, in this study, a UV lamp was installed inside the ventilation duct to indirectly apply the mechanism employed by TiO_2 photocatalysts in indoor spaces.

Third, a limitation of this study is that the ventilation system used in the experiment is an energy recovery ventilation system, which introduces outdoor air in addition to internal circulation. Therefore, further research is necessary to compare the performance of different filters in reducing gaseous pollutants when natural ventilation is introduced. Natural ventilation can decrease pollutant concentrations by diluting indoor air with clean outdoor air, which can affect the performance of filtration methods based on decomposition and adsorption. Therefore, to confirm the effectiveness of different filtration methods, it is essential to conduct performance comparisons under conditions where pollutants are diluted through natural ventilation.

Finally, if the length, weight, and application method of the TiO_2 photocatalytic filter used in this study are improved, there is potential to apply the pollutant reduction effect of the TiO_2 photocatalyst in various indoor environments, where the use of UV rays may be restricted. Further

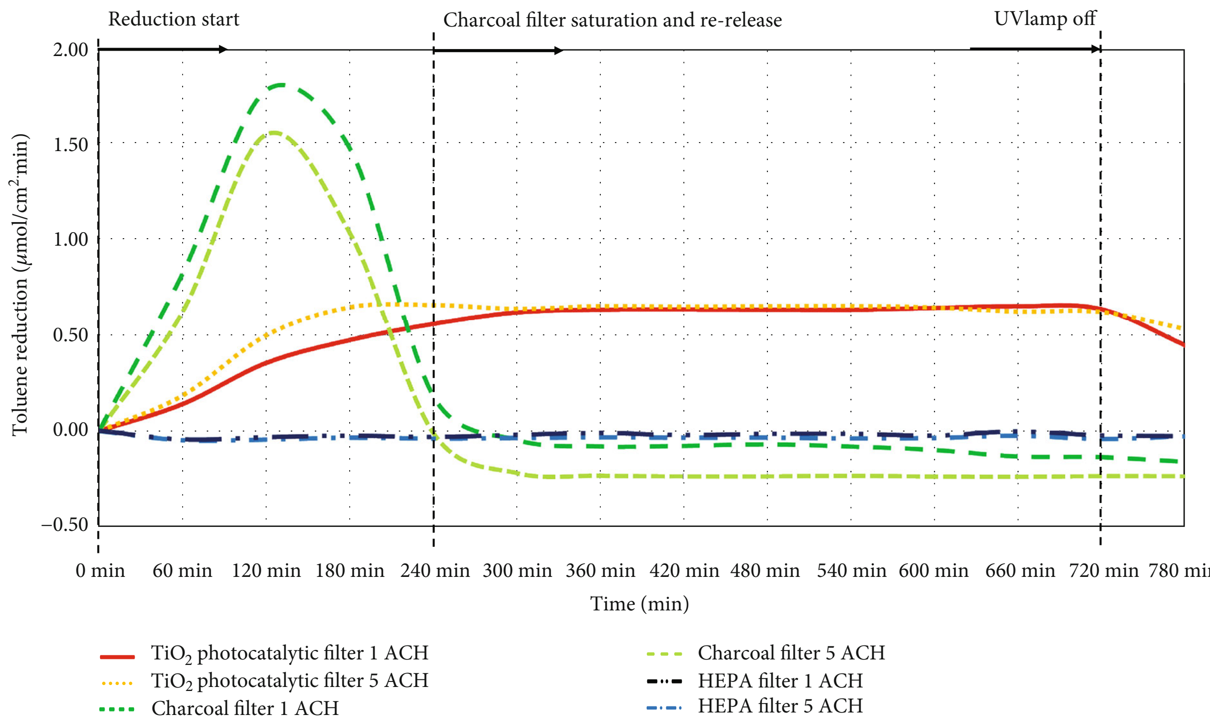


Figure 10: Reducing pollutants over time depending on ventilation and filter type.

Table 11: Reducing pollutants over time depending on ventilation and filter type.

Time	Filter type					
	TiO_2 photocatalytic		Charcoal		HEPA	
	1 ACH	5 ACH	1 ACH	5 ACH	1 ACH	5 ACH
0 min (UV-on)	0.00	0.00	0.00	0.00	0.00	0.00
60 min (UV-on)	0.14	0.19	0.62	0.83	-0.05	-0.05
120 min (UV-on)	0.36	0.50	1.55	1.79	-0.04	-0.03
180 min (UV-on)	0.48	0.65	1.04	1.48	-0.03	-0.03
240 min (UV-on)	0.56	0.66	-0.01	0.18	-0.04	-0.03
300 min (UV-on)	0.62	0.64	-0.22	-0.05	-0.04	-0.02
360 min (UV-on)	0.64	0.65	-0.23	-0.08	-0.03	-0.01
420 min (UV-on)	0.64	0.65	-0.24	-0.08	-0.03	-0.02
480 min (UV-on)	0.64	0.65	-0.24	-0.07	-0.03	-0.02
540 min (UV-on)	0.63	0.66	-0.23	-0.08	-0.04	-0.02
600 min (UV-on)	0.64	0.65	-0.24	-0.10	-0.04	-0.02
660 min (UV-on)	0.65	0.63	-0.24	-0.13	-0.02	0.00
720 min (UV-off)	0.64	0.62	-0.24	-0.14	-0.04	-0.02
780 min (UV-off)	0.45	0.53	-0.24	-0.16	-0.03	-0.03

Symbols (-) indicate rerelease (unit: μmol/cm^2·min).

advancements in the design and application of TiO_2 photocatalytic filters could broaden their potential for reducing indoor gaseous pollutants beyond the limitations of UV rays.

4. Conclusion

In this study, we utilized a ventilation system designed to effectively remove pollutants from indoor air in situations where ventilation is challenging. We evaluated the performance of HEPA, charcoal, and TiO_2 photocatalytic filters in reducing gaseous pollutants via a mock-up experiment, and the findings are summarized as follows.

First, we designed and fabricated a tubular TiO_2 photocatalytic filter, which was used in conjunction with HEPA and charcoal filters that are commonly used in existing ventilation systems. The pollutant reduction performance of each filter was evaluated using toluene gas as a representative indoor pollutant. We conducted accelerated tests by applying ventilation system air volumes that circulated the mock-up volume once and five times per hour and assessed the sustainability of the filter performance.

Second, among the three filters used in the experiment, the HEPA filter was found to be ineffective in reducing gaseous pollutants. In contrast, the activated carbon filter demonstrated the highest reduction performance across all variables tested in the experiment. However, as the pollutant concentration started increasing again after reaching the minimum concentration, the sustainability of its performance was limited, which suggested that the activated carbon filter became saturated because of pollutant adsorption.

Third, the TiO_2 photocatalytic filter demonstrated a pollutant reduction performance that was approximately 50% lower than that of the activated carbon filter in the experiment; however, its pollutant decomposition performance was sustained over a longer time. It is anticipated that even better reduction results can be achieved by employing methods to increase the content or reactivity of the TiO_2 photocatalyst, such as doping.

This experimental study highlights that different filter types, including those based on TiO_2 photocatalysts and UV rays, can effectively reduce gaseous pollutants and retain their performance over time in indoor spaces. The findings of this study can serve as valuable baseline data for the development of methods utilizing TiO_2 photocatalysts in indoor spaces, with the aim of improving indoor air quality in apartment buildings through pollutant decomposition and adsorption, even in situations where dilution ventilation is challenging because of air pollution.

Data Availability

Data are available on request.

Conflicts of Interest

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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