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Antimicrobial Air Filter as a Sustainable Alternative to Ultraviolet Germicidal Irradiation for Inactivating Airborne Microorganisms in Building Ventilation System

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Abstract. Indoor air quality is critical as people spend most of their time inside. The COVID-19 pandemic intensified concerns over airborne pathogens, leading many buildings to install ultraviolet germicidal irradiation (UVGI) in ventilation systems. However, UVGI is often ineffective due to short pathogen exposure times and energy intensive. This study proposes a sustainable alternative: antimicrobial air filters. These fibrous filters trap microorganisms, prolonging contact with the microbicidal agent to inactivate them. The approach was tested in two Hong Kong office buildings, comparing UVGI with ordinary filters against disabled UVGI with antimicrobial filters. Air sampling upstream and downstream measured viable microorganism levels via culturing and counting. The antimicrobial filters outperformed UVGI, achieving 8.1–93.3% greater microbial reduction. They also eliminated 2,700W and 750W of UVGI power per floor, saving the buildings 574,000 kWh and 344 tonnes of carbon annually. Global adoption could save 2,358.5 million kWh and reduce CO_2 by 1.07 million tonnes yearly. This strategy offers superior performance, lower costs, and significant carbon reduction, confirming antimicrobial filters as a viable alternative to in-duct UVGI.

1 Introduction

People spend most of their time indoors for living and working, making indoor air quality and its control important aspects of health and well-being. The COVID-19 pandemic has heightened concerns about the transmission and control of airborne microorganisms in indoor spaces.

Building ventilation systems play a crucial role in managing indoor airborne disease transmission. To reduce air conditioning energy consumption, most mechanical ventilation systems recirculate a portion of indoor air, which can also circulate pathogens released by an infected occupant throughout the building. While these systems are typically equipped with

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air filters in the air handling unit (AHU) that can capture some airborne microorganisms, they are not 100% effective.

To compensate for this limitation, ultraviolet germicidal irradiation (UVGI) devices are increasingly installed for enhanced air disinfection. However, research shows that UVGI is often ineffective in ventilation systems. Effective microbial inactivation requires sufficient UV exposure time, but the high airflow speeds typically prevent pathogens from remaining in the irradiated zone long enough [1]. Furthermore, UVGI systems are energy-intensive, increase air resistance in the ventilation system, and incur significant capital and operational costs, leading to higher overall energy consumption, carbon emissions, and expenses.

This study investigated the feasibility of adopting antimicrobial air filters in building ventilation systems as an alternative to UVGI. The findings were validated through field measurements within operational ventilation systems equipped with UVGI in two commercial buildings in Hong Kong. Microbiological air sampling was conducted to analyze disinfection efficiency. Additionally, the potential for energy savings and carbon emission reductions from replacing UVGI with antimicrobial filters was evaluated.

2 Literature Review

2.1 Indoor Transmission and Control of Airborne Microorganism

Pathogenic microorganisms are released into indoor air primarily through human respiratory activities such as coughing, sneezing, speaking, and even breathing, where they are expelled as aerosols or droplets that desiccate into droplet nuclei, as well as through aerosolization from contaminated surfaces or water systems. Once airborne, mechanical ventilation systems can inadvertently aid their transmission by actively distributing contaminated air throughout a building's interior spaces via ductwork, especially if these systems lack adequate filtration or recirculate air without proper treatment, effectively creating pathways for pathogens to reach susceptible individuals.

Key control strategies to mitigate this risk include air filtration, which employs High-Efficiency Particulate Air (HEPA) filters or MERV-rated filters in HVAC systems to physically capture and remove airborne particles [2], and Ultraviolet Germicidal Irradiation (UVGI). UVGI is deployed in two primary configurations: upper-room UVGI, where fixtures mounted on walls or ceilings irradiate the upper air zone to inactivate microorganisms without exposing occupants, and in-duct UVGI, which installs lamps within air handling units or ducts to disinfect air as it passes through the ventilation system, thereby reducing the airborne microbial level before it is supplied to occupied spaces.

While some studies have reported a significant reduction in viable microorganisms within spaces equipped with upper-room UVGI [3], other research indicates that many pathogenic microbes require at least several seconds of exposure to high-intensity ultraviolet light for effective inactivation [1]. However, the airflow velocity within mechanical ventilation systems typically reaches several meters per second [2]. This high flow rate significantly reduces the dwell time of airborne microorganisms in the irradiation zone, thereby casting doubt on the practical efficacy of in-duct UVGI for reliably disinfecting airborne microorganisms.

In contrast, air filters are installed within the ventilation system to intercept all recirculated air, providing a reliable method of physical removal where efficiency is determined by the filtration class. A key concern with this approach, however, is the possibility that captured particles may detach from the filter media, a topic explored further in the next section.

2.2 Entrapment and Reentrainment Mechanisms of Air Filter

Particles captured by an air filter are not necessarily permanently entrapped on its fibers. A common misconception about air filtration is that particles are merely "sieved" out of the air stream, implying that once collected, they cannot re-enter it. However, sieving is only one of several filtration mechanisms, and it primarily applies to particles larger than the openings between fibers [4]. Smaller particles are typically removed from the air stream when microscopic or molecular forces attract and hold them to the fiber surfaces [4]. Because this adhesion can be disrupted by factors such as airflow fluctuations or fiber vibration, captured particles can detach and re-enter the air stream, a phenomenon known as re-entrainment.

Re-entrainment occurs continuously as air passes through a filter, even at velocities as low as 0.4 m/s, with detachment rates increasing at higher airflow speeds [5]. Research shows that the aerodynamic force needed to detach a particle from a filter fiber is considerably greater than the force required via vibration [6]. However, airflow itself can also induce vibration, stretching, and compression of filter fibers [6]. Re-entrainment is observed even in HEPA filters, detachment rates reaching up to 7% was observed under tested conditions in preloaded HEPA filters [7]. In typical ventilation filters, one study reported that up to 13% of fungal spores could be re-entrained at air velocities exceeding 3 m/s [8].

When viable bioaerosols are re entrained from air filters, they pose a potential risk of airborne infection in indoor environments. Antimicrobial air filters can significantly reduce this risk, as captured microorganisms remain in prolonged contact with the filter media, allowing active ingredients—coated on or blended into the filter fibers—to efficiently inactivate them.

2.3 Energy Consumption of Building Ventilation and UVGI

The building sector accounts for one-third of the world's total energy consumption and carbon emissions [9]. Despite new initiatives to design sustainable buildings, emissions reduction from the sector have been lagging, with floor area growing faster than efficiency [9]. To achieve sustainability, there is therefore an urgent need to improve the energy efficiency of the massive stock of existing structures.

Ventilation systems are a primary focus for reducing building energy consumption and carbon emissions. Heating, ventilation, and air conditioning (HVAC) systems can account for up to 70% of a building's total energy use, with ventilation alone responsible for approximately 20% in dense urban environments such as Singapore. In mechanical ventilation systems, the main energy-consuming component is typically the fan motor, which has a rated power ranging from several kilowatts to nearly one hundred kilowatts. By comparison, an in-duct UVGI system typically has a rated power of several hundred watts to a few kilowatts, depending on the scale of the ventilation system it serves. Although UVGI systems consume significantly less power than fan motors, adopting lower-power alternatives remains desirable to further enhance building sustainability.

3 Materials and Methods

3.1 The Buildings and Their Ventilation Systems

The study utilized return air handling units (AHU) from two high-rise commercial office towers in Hong Kong. Each building features standardized floor plans with mechanical ventilation systems identical to each floor; every floor is equipped with between one and four return air AHUs.

The return air AHUs perform three critical functions:
1. Particulate filtration
2. Return air cooling
3. Fresh air mixing with outdoor supply

All AHUs are equipped with:
- UVGI with UV-C light tube (Linear Fluorescent Lamps, LFL) arrays
- Electronically commutated fans or variable speed drive (VSD) on a fan motor

Key building characteristics and detailed ventilation system specifications are provided in Table 1.

Table 1. Information on the two buildings and the ventilation systems

Parameter	Building #1	Building #2
Type	Commercial office building	Commercial office building
No. of floors and lettable floor area	39 floors, approximately 1,343.5m2/floor	25 floors, approximately 1,340m2/floor
Ventilation strategy	Air circulation through AHU, fresh air intake through primary AHU. 4 return air AHU/floor on typical floor (2 larger units and 2 smaller units), and primary AHU/floor on specific floors	Air circulation through AHU, fresh air intake through primary AHU. 1 return air AHU/floor, and 1 primary AHU/floor
Power of AHU fan motor (kW)	Return Air AHU: 3 electronically commutated fans, 6.8kW each, total 20.4kW	Return Air AHU: 4 electronically commutated fans, 5.25kW each, total 21kW
Operating time of the AHUs	60.5hour/week, 52week/year	60.5hour/week, 52week/year
UVGI system	UV-C light tubes, total power 750W for smaller AHU, 1350W for larger AHU	UV-C light tubes, total power 750W

3.2 Sampling AHUs and Their Filter Section

Microbiological air samplings were conducted in two of the AHUs (Saiver Model A1(C)1610H-2250W) in Building #1 and one of the AHUs (Saiver Model A1(C)1450H-

3050W) in Building #2. The AHUs in Building #1 each have has a designed total static pressure of 1,486Pa and a total fan power of 20.4kW. The AHU in Building #2 has a designed total static pressure of 1,508Pa and a total fan power of 21kW. The three AHUs are in separate plant rooms. In the ventilation process, their return air and fresh air were mixed in each plant room before entering the inlet of the return air AHU.

The AHUs incorporate a two-layer filtration system:

1. Primary filtration:
- Reusable metal mesh filters (6 pieces for the sampling AHUs in Building #1, 10 pieces for the sampling AHU in Building #2)
- G4 grade (EN779 standard)
- Targets large particulate matter (>10μm) and coarse dust
2. Secondary filtration:
- Pocket-type filters (same quantity with the reusable metal mesh filters for the 3 AHUs)
- MERV13 class (ASHRAE52.2 standard)
- Aims at capturing fine particles

Fig. 1 shows the photos of the air filters in the AHUs' filter section.

(a)

(b)

Fig. 1 Air filters in the AHUs' filter section for (a) AHUs in Building #1, and (b) AHU in Building #2. The first layer of washable metal prefilters can be seen.

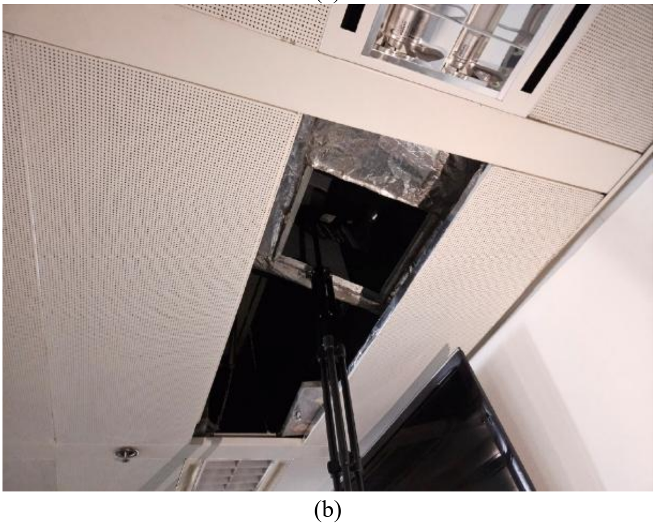
Microbiological air sampling involved two scenarios. First, for the UVGI scenario, new clean pocket-type filters were installed, and the UVGI system was activated. Second, for the antimicrobial air filter scenario, these filters were replaced with antimicrobial filters of the same filtration class, and the UVGI systems were turned off. The antimicrobial coating used silver nitrate as its active agent [10]. This approach allowed for a direct comparison between the two strategies under equivalent physical filtration efficiency.

3.3 Sampling Method and Equipment Used

Sampling was conducted at two locations: upstream (before the air filters and UVGI system) and downstream (after the filters and UVGI system). At each location, 200 liters of air were collected over a two-minute period. For each scenario, two airborne microbe samplers (Microbial Impactor, MicroBio Sampler Model MB2 Rev. 7.1) were deployed simultaneously to capture concurrent samples from both locations. Airborne microbes, which exist naturally in the air, were collected onto the petri dishes inside the air samplers. Following collection, the petri dishes from the samplers were processed using standard bacterial culturing and colony counting techniques. The percentage reduction in colony-forming units (CFUs) from upstream to downstream was then calculated and analyzed for each scenario.

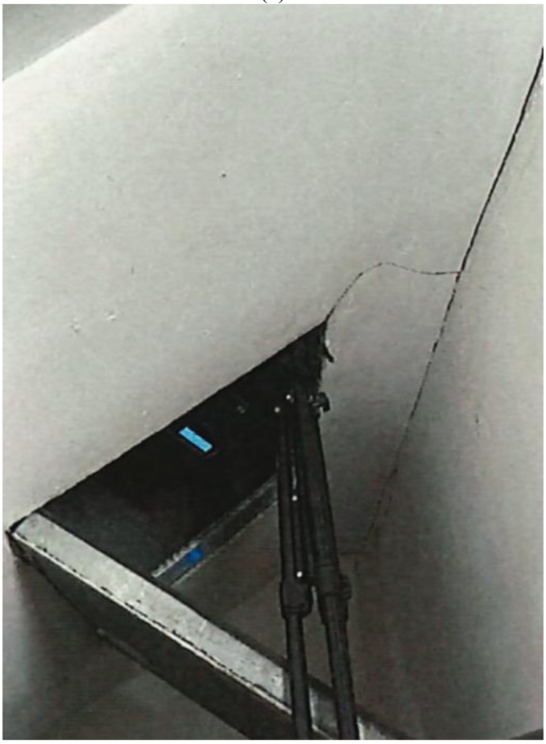
Microbiological air samplings were conducted on 18th March, 2024 for Building #1 and on 10th January, 2025 for Building #2. Samplings were taken within a single day for each building to ensure minimal environmental variability. The AHUs were set to have consistent airflow rate during the sampling. Fig. 2 shows the photos of the air sampling locations.

(a)



(b)

(c)



(d)

Fig. 2 Photos of the sampling locations (a) Upstream of Building #1 AHU, (b) Downstream of Building #1 AHU, (c) Upstream of Building #2 AHU, and (d) Downstream of Building #2 AHU

4 Result and Discussion

4.1 Airborne Microbe Reduction by the Antimicrobial Air Filters verse UVGI

The airborne microbe counts in terms of CFU/m³ and the % reduction of the two scenarios for the 3 AHUs are summarized in Table 2.

Table 2. Microbiological air sampling results

Building #1 AHU No. 1			
Scenario	Upstream (CFU/m^3)	Downstream (CFU/m^3)	% Reduction
UVGI	108	13	88.0%
Antimicrobial Air Filter	45	1	97.8%
Building #1 AHU No. 2			
Scenario	Upstream (CFU/m^3)	Downstream (CFU/m^3)	% Reduction
UVGI	195	33	83.1%
Antimicrobial Air Filter	98	10	89.8%
Building #2 AHU			
Scenario	Upstream (CFU/m^3)	Downstream (CFU/m^3)	% Reduction
UVGI	38	19	50.0%
Antimicrobial Air Filter	90	3	96.7%

Note: UVGI scenario refers to UVGI system activated and the AHU operating with conventional air filters; Antimicrobial Air Filter scenario refers to UVGI system deactivated and the AHU operating with antimicrobial air filters

All three AHUs in the two buildings showed higher CFU/m^3 reduction rates with antimicrobial air filters than with UVGI, with improvements ranging from 8.1% to 93.3%. This indicates that antimicrobial air filters could replace UVGI systems while delivering better airborne disinfection performance.

4.2 Energy Saving and Carbon Emissions Reduction by Replacing UVGI with Antimicrobial Air Filters

By replacing the UVGI system with antimicrobial air filters, each floor in Building #1 can save 4,200 W of electricity, resulting in a total building-wide reduction of 163.8 kW. For Building #2, the per-floor saving is 750 W, totalling 18.75 kW across the building. Annually, this would translate to electricity savings of approximately 515,000 kWh for Building #1 and 59,000 kWh for Building #2. Based on the utility provider's emission factor of 0.6 kg CO_2e/kWh, these savings equate to a reduction of around 309 tonnes of carbon emissions for Building #1 and 35 tonnes for Building #2. The significantly greater energy and emission reductions in Building #1 are due to its higher number of UVGI units per floor and more floors compared to Building #2.

The global potential for reducing energy consumption and carbon emissions by replacing UVGI with antimicrobial air filters was evaluated using market report and literature data. Table 3 summarizes the parameters used in the global-scale analysis.

Table 3. Parameters used in the global-scale analysis

Parameter	Value	Source
UV disinfection equipment market size	USD 6.8 billion in 2025	Market report [11]
UV lamps market size in UV disinfection equipment market	USD 2.5 billion in 2025	Market report [11]
Market share of In-duct UVGI system	27%	Journal Article [12]
Retail price of UV lamps per wattage	USD 1.8/W	Based on the retail prices of 30 different UV (LFLs) on Amazon
UVGI system Installation share	60% are installed in healthcare facilities; 40% on others	Journal Article [13]
Operating hours of the UVGI system	365 days, 24 hours in healthcare facilities; 250 days, 11 hours/day for other facilities	Reasonable assumption
Carbon emission factor per kWh of electricity	0.445 kgCO2e/kWh	Global average [14]
% of usage stage carbon emission to lifetime carbon footprint for LFL	98.19%	Journal Article [15]

The analysis estimated the global energy and carbon savings from replacing in-duct UVGI systems with antimicrobial air filters. Using the market size of in-duct UVGI systems and other parameters summarized in Table 3, we calculate that this replacement could save approximately 2,358.5 million kWh of electricity annually, leading to a reduction of about 1.07 million tonnes of carbon emissions per year. This is likely a conservative estimate, as the carbon footprint of additional UVGI components, such as ballasts and metal holding frames, was not considered.

5 Conclusion

This study experimentally verified antimicrobial air filters as a viable, high-efficiency alternative to in-duct UVGI through microbiological air sampling in two operational office buildings. The antimicrobial filters outperformed the UVGI systems in airborne microbe reduction across all three sampled AHUs. Replacing the UVGI systems yielded an annual energy saving of 574,000 kWh and a reduction of 344 tonnes in carbon emissions for the sampled buildings. Extrapolated globally, this replacement could save an estimated 2,358.5 million kWh of electricity and reduce carbon emissions by about 1.07 million tonnes annually. As an easy retrofit to existing ventilation systems, antimicrobial filters also offer economic incentives to building owners by avoiding UVGI installation costs, lowering operational expenses, and contributing significantly to carbon reduction goals.

References

1. C.C. Tseng, C.S. Li, Inactivation of virus-containing aerosols by ultraviolet germicidal irradiation. Aerosol Sci. Technol. **39**, 12 (2005)
2. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ANSI/ASHRAE Standard 52.2-2017 (ASHRAE, Atlanta, GA, 2017)
3. C.B. Beggs, E.J. Avital, Upper-room ultraviolet air disinfection might help to reduce COVID-19 transmission in buildings: a feasibility study. PeerJ. **8**, e10196 (2020)
4. W.C. Hinds, Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles (John Wiley & Sons, New York, NY, USA, 1999)
5. L. Poggemann, J. Meyer, A. Dittler, A novel method to investigate detachment of particulate structures from an elastic single fiber at low gas flow velocities. J. Aerosol Sci. **156**, 105785 (2021)
6. J. Visser, Adhesion of dust and powder. J. Colloid Interface Sci. **94**, 298 (1983)
7. Y. Yamada, A. Koizumi, K. Miyamoto, Re-entrainment of 239PuO2 particles captured on HEPA filter fibres. Radiat. Prot. Dosim. **82(1)**, 25-29 (1999)
8. E. Jankowska, T. Reponen, K. Willeke, S.A. Grinshpun, K-J. Choi, Collection of fungal spores on air filters and spore reentrainment from filters into air. J. Aerosol Sci. **31**, 969 (2000)
9. International Energy Agency, Breakthrough Agenda Report (IEA, 2025)
10. G.N. Sze-To, Air filtration systems and methods of forming an air filtration system. U.S. Patent US12427464B2 (2025)
11. Strategic Revenue Insights Inc., UV Disinfection System Market Size, Future Growth and Forecast 2033 (2026). Available: https://www.strategicrevenueinsights.com/industry/uv-disinfection-system-market
12. J. Ye, Z. Ai, F. Liu, P. Wargocki, A critical review of in-duct ultraviolet germicidal irradiation systems: Mechanisms, challenges, and future directions. Process Saf. Environ. Prot. **195**, 106840 (2025)
13. F. Memarzadeh, R.N. Olmsted, J.M. Bartley, Applications of ultraviolet germicidal irradiation disinfection in health care facilities: Effective adjunct, but not stand-alone technology. Am. J. Infect. Control **38**, S13 (2010)
14. International Energy Agency, Electricity 2025: Analysis and forecast to 2027 (IEA, 2025)
15. S. Chen, J. Zhang, Environmental Impacts of Compact Fluorescent Lamps and Linear Fluorescent Lamps in China. in International Proceedings of Economics Development and Research. vol. 26, ed. by Chen Dan (2016), pp. 359