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ARTICLE

Design and performance analysis of a MopFan-based multi-stage air purification system for indoor pollution control

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Abstract

Indoor air pollution poses a significant threat to global health, contributing to respiratory and cardiovascular diseases and exacerbating environmental challenges. Addressing this critical issue, this study evaluates the performance of a novel air purification device, the MopFan – a system integrating advanced filtration technologies, including high-efficiency particulate air filters, photocatalytic oxidation, and bio-aerogel materials, principally designed to mitigate gaseous pollutants. The MopFan was tested under controlled environmental conditions across three room sizes and varying ventilation states to assess its efficacy in removing volatile organic compounds (VOCs) and formaldehyde (HCHO), common indoor air pollutants. Employing ethanol vapour as pollutant, the results demonstrated reductions in gaseous pollutant concentrations – specifically, VOCs and HCHO – of up to 65% in small, enclosed spaces, with performance influenced by room size and ventilation. The device's multi-stage filtration system effectively decomposed pollutants, leveraging TiO_2-coated fibres activated by ultraviolet C light and bio-aerogel filters for enhanced antiviral and chemical filtration. Particularly, ventilation plays a critical role in pollutant dispersion. Further comparative analysis is recommended to ascertain whether such a reduction suffices to meet the current regulatory guidelines. This study highlights the MopFan's potential as a sustainable, scalable solution for improving indoor air quality (IAQ) in diverse settings. The MopFan's innovative design, combining eco-friendly materials and advanced filtration methods, offers a pathway to mitigate indoor air pollution's health impacts, aligning with global sustainability and public health objectives. This research advances the scientific understanding of IAQ interventions and supports the development of effective, scalable solutions.

Keywords: Indoor air pollution; Air purification technologies; Photocatalytic oxidation; Bio-aerogel filtration; Sustainable air quality solutions

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1. Introduction

Indoor air pollution represents a significant environmental health challenge, profoundly impacting global morbidity and mortality. According to the World Health Organization,[1] approximately 3.2 million premature deaths were attributed to indoor air pollution in 2020 alone, including over 237,000 deaths among children under the age of five.[1] These alarming statistics underscore the pervasive and detrimental effects of poor indoor air quality (IAQ) on human health, particularly in vulnerable populations. The burden is disproportionately borne by low-income and middle-income countries, where reliance on solid fuels such as wood, coal, and animal dung for cooking and heating is prevalent.[2] The combustion of these materials releases harmful pollutants, including particulate matter (PM2.5), carbon monoxide (CO), and polycyclic aromatic hydrocarbons, leading to elevated indoor pollutant concentrations far exceeding safe limits.[3]

However, indoor air pollution is not confined to resource-limited settings. In industrialised nations, despite advanced infrastructure and energy-efficient building designs, IAQ remains a pressing issue. Paradoxically, the same innovations aimed at improving energy efficiency, such as enhanced insulation and reduced air exchange rates, often exacerbate pollutant build-up indoors.[4] Pollutants such as volatile organic compounds (VOCs), nitrogen dioxide (NO_2), and ozone (O_3) are commonly emitted from modern building materials, furniture, and household products. Moreover, inadequate ventilation in energy-efficient buildings can exacerbate the accumulation of these pollutants. Sources of indoor pollution in such settings are diverse, encompassing off-gassing from synthetic building materials, household cleaning agents, personal care products, and inadequate ventilation.[5] In addition, tobacco smoke, microbial contaminants, and emissions from appliances contribute to the complex mixture of indoor air pollutants.[6] The COVID-19 pandemic has further highlighted the importance of IAQ as prolonged indoor stays and concerns about airborne pathogen transmission have increased awareness and demand for clean indoor air.[7,8]

1.1. Health implications of indoor air pollution

The health implications of indoor air pollution are profound and multifaceted. Fine particulate matter (PM2.5), for instance, is a well-documented risk factor for respiratory and cardiovascular diseases. Chronic exposure has been linked to the development of chronic obstructive pulmonary disease (COPD), lung cancer, and ischemic heart disease.[9] PM2.5 is known to cross into the bloodstream, causing inflammation and exacerbating conditions such as asthma, bronchitis, and COPD. In addition, long-term exposure to fine particulates increases the risk of cardiovascular diseases and lung cancer. Furthermore, VOCs such as formaldehyde (HCHO) and benzene, commonly emitted from furniture, carpets, paints, and adhesives, are known to cause both acute and chronic health effects, ranging from respiratory irritation to carcinogenicity.[10,11] VOCs, such as HCHO and benzene, are classified as carcinogens and contribute to both short-term effects such as eye irritation and long-term risks such as organ toxicity and malignancies. Nitrogen dioxide and ozone further exacerbate respiratory illnesses and reduce lung function, especially in vulnerable populations.[12,13] Microbial contaminants, including fungal spores and bacteria, exacerbate allergic reactions, asthma, and other respiratory conditions.[14] Children, the elderly, and individuals with pre-existing health conditions are particularly susceptible to these adverse outcomes.[15]

The urgency of addressing IAQ is magnified by lifestyle patterns that have evolved over the decades. Studies indicate that individuals in developed countries spend up to 90% of their time indoors, a figure that has likely increased following the COVID-19 pandemic due to prolonged periods of remote work and schooling.[16] The pandemic also heightened awareness of airborne pathogen transmission, further emphasising the importance of maintaining clean and healthy indoor air. This recognition has catalysed advancements in IAQ technologies, with air purification systems emerging as a critical intervention.[17]

Among the various air purification methods, photocatalytic oxidation (PCO) stands out for its efficacy and versatility. PCO employs a photocatalyst, typically titanium dioxide (TiO_2), which is activated by ultraviolet (UV) light. This activation generates reactive oxygen species (ROS) such as hydroxyl radicals and superoxide ions, capable of oxidising and decomposing organic pollutants, including VOCs, HCHO, and pathogenic microorganisms.[18] Unlike conventional high-efficiency particulate air (HEPA) filters, which merely trap pollutants, PCO systems chemically degrade them into benign by-products such as water and carbon dioxide.[19] This attribute makes PCO particularly attractive for applications requiring the elimination of odours, VOCs, and airborne pathogens without secondary pollution.[20]

Despite its potential, the practical implementation of PCO technology in air purification devices has faced challenges. These include the formation of undesirable by-products such as ozone, variability in performance under different environmental conditions, and the need for optimization of catalytic surfaces.[21] Innovations such as the MopFan-based air purifier aim to address these limitations by enhancing the surface area for photocatalytic reactions and ensuring efficient airflow through the device.

This study focuses on evaluating the efficacy of a MopFan-based air purifier equipped with TiO_2-coated fibres and UVC irradiation. By systematically examining its performance in removing VOCs and HCHO under controlled conditions, this research seeks to contribute to the growing body of evidence supporting advanced air purification technologies. Moreover, it highlights the critical role of innovative design and material selection in achieving sustainable solutions to indoor air pollution.

The findings of this investigation aim to inform both the scientific community and policymakers about the potential of PCO-based air purifiers to mitigate the health risks associated with indoor air pollution. By addressing the pressing need for cleaner indoor air, this work aligns with broader public health goals and sustainability initiatives, ultimately contributing to the improvement of human well-being in diverse living environments.

1.2. Traditional air purification methods

Conventional air purification systems, including HEPA filters and activated carbon filters, have been widely adopted to mitigate indoor air pollution. HEPA filters are particularly effective in capturing particulate matter, removing over 99.97% of particles with diameters as small as 0.3 microns. Activated carbon filters, on the other hand, specialise in adsorbing VOCs and odours. While these methods provide substantial relief, they primarily act as containment solutions, requiring regular maintenance and replacement. This limitation highlights the need for advanced air purification technologies that actively degrade pollutants.[22]

1.3. PCO: Mechanism and application

PCO represents an innovative approach to air purification, leveraging the chemical properties of a photocatalyst, typically TiO_2. When exposed to UV light, TiO_2 becomes activated, producing ROS such as hydroxyl radicals and superoxide ions. These ROS are potent oxidizers, capable of decomposing organic pollutants into benign by-products such as carbon dioxide and water. PCO offers a dual advantage: it effectively neutralises both particulate and gaseous pollutants and eliminates biological contaminants, including bacteria and viruses.[13,19]

Numerous studies have demonstrated the efficacy of PCO technology in reducing indoor pollutants. For example, PCO systems equipped with TiO_2-coated surfaces have been shown to remove over 70% of VOCs and HCHO under controlled conditions. However, challenges such as the potential formation of secondary pollutants, including ozone, and the dependence on optimal UV light intensity and catalyst surface area, require further exploration to maximise its practical applications.[23]

1.4. Advances in PCO-based air purifiers

Recent innovations aim to enhance the efficiency and sustainability of PCO systems. Novel designs such as the MopFan-based air purifier integrate TiO_2-coated fibres into a mop-like structure, maximising the surface area for photocatalytic reactions.[24] This configuration improves the interaction between air pollutants and the catalytic surface, enhancing pollutant removal efficiency. The combination of UVC irradiation with TiO_2-coated surfaces has shown promising results in degrading VOCs and pathogens while minimising secondary by-product formation.[25]

Despite these advancements, practical implementation challenges persist. Variability in environmental conditions, including humidity and airflow rates, can influence the effectiveness of PCO systems. Furthermore, the durability and regeneration capacity of the catalytic surfaces remain areas of active research, as does the potential for integrating PCO technology into existing ventilation systems for large-scale applications.[19,26]

2. System design and manufacture

The air purification device under test, the "MopFan," is a prototype engineered specifically for this study, integrating advanced filtration technologies aimed at effectively removing chemical and biological contaminants from indoor air environments. The device's design is the result of innovative research and development efforts, incorporating unique components not typically found in commercial air purifiers (Figure 1).

2.1. Description of components

2.1.1. Brush strips

The initial stage of the MopFan design focused on selecting suitable organic fibres for the filtration system. After extensive research and testing, Tampico fibres were

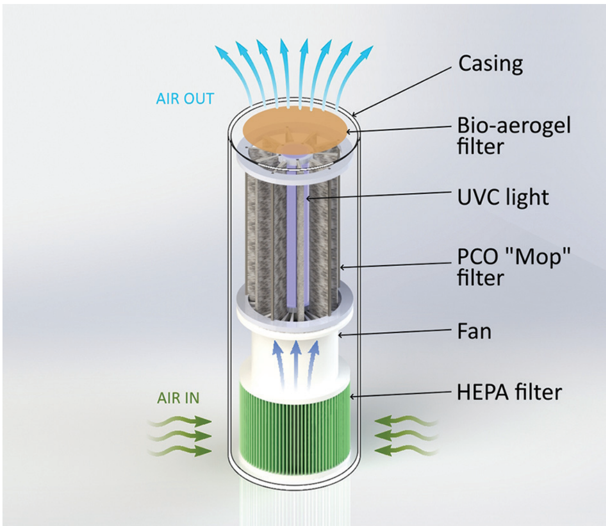

Figure 1. Concept diagram of the MopFan
Abbreviations: HEPA: High-Efficiency Particulate Air; PCO: Photocatalytic oxidation; UVC: Ultraviolet C.

chosen for their exceptional properties.[27] These fibres are highly porous, allowing them to effectively absorb the TiO_2 coating, which is crucial for the air purification process. The natural texture of these organic fibres also facilitates better adhesion of the coating, enhancing their performance without the need for additional surface treatment.

The brushes utilised were manufactured by Koti Dawson Ltd. The brushes are designed to hold the fibres in place using a steel rib and cross wire structure, ensuring high fibre density and stability. These brushes measure 400 mm in length with fibres extending 8 – 10 cm, providing a large surface area for air purification (Figure 2).

2.1.2. Coating

The coating process for the MopFan fibres was streamlined due to the inherent properties of the selected organic material. Unlike previous iterations that required sanding, the organic fibres' natural texture facilitated the coating adhesion.[24] The preparation of the TiO_2 solution involved the following steps:

1. Solution preparation: A fixed amount of TiO_2 was mixed in water to create a uniform and stable solution. This preparation has been described by Tapia-Brito *et al.*[24]
2. Immersion: The brushes were submerged in the TiO_2 solution. This immersion was repeated twice to ensure a consistent and thorough coating around the fibres.
3. Drying: After each immersion, the brushes were allowed to dry completely at room temperature, ensuring the formation of a thick and durable TiO_2 layer.

2.1.3. Fan

The MopFan utilises the HG Power 6 Inch Reversible Extractor Fan to ensure effective air circulation through the device (Figure 3). This fan, which operates at 30W, provides a maximum airflow capacity of 185 m^3/h, the fan is suitable for efficient air exchange in various indoor environments. Despite its robust performance, it operates at a low noise level of approximately 35 dB, ensuring quiet operation and enhancing user comfort. The fan is constructed from high-quality ABS plastic, making it durable and resistant to corrosion, which ensures long-term reliability.

Strategically installed at the base of the MopFan, the fan ensures a steady flow of air through the device. Air enters the unit, passes through the TiO_2-coated fibre brushes for purification, and is then expelled back into the room.

2.1.4. Filtration system components

The device employs a sequential multi-stage filtration process, combining mechanical and photonic methods to enhance purification efficiency. Each stage is designed to target specific types of contaminants, ensuring comprehensive air cleaning.

- Pre-filter: Air enters the device through the specially designed openings in the 3D-printed housing. These apertures act as a passive pre-filter, physically blocking large particles such as hair and lint. By preventing these larger contaminants from reaching the internal filters, the pre-filtering provided by the housing reduces the particulate load on subsequent stages, thereby enhancing their efficiency and extending their operational lifespan.
- HEPA filter: Following the initial pre-filtering, the air passes through a HEPA filter conforming to Class H13 specifications as per BS EN 1822 – 1:2019. The HEPA filter is composed of densely packed fibrous material capable of capturing 99.95% of particles as small as 0.3 µm. This includes fine particulates such as pollen, mold spores, and certain bacteria. The mechanical filtration provided by the HEPA filter significantly reduces airborne particulate matter, contributing to improve IAQ (Figure 4).
- UVC light: The next stage involves UV germicidal irradiation (UVGI) within a sealed UVC light

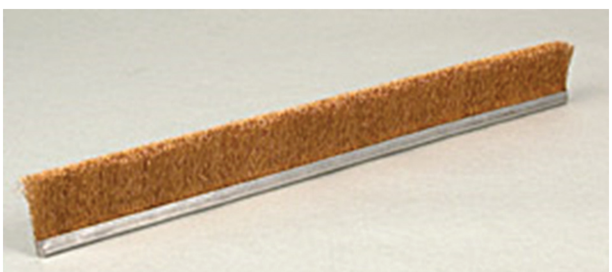

Figure 2. Tampico fibre strip brush

Figure 3. Extractor fan

chamber. Air is exposed to 185 nm UVC light, known for its germicidal properties. The UVC photons disrupt the nucleic acids of any residual microorganisms, rendering them incapable of replication and infection. The UVC system is enclosed in a sealed chamber to prevent radiation leakage and includes protective housing and a safety interlock mechanism to prevent accidental exposure (Figure 5).

With a lifespan of 9,000 h, the UVC lamp is made from high-quality quartz glass and can be easily replaced. Adequate ventilation is provided to safely dissipate ozone generated during operation. The UVC light also serves another key function: Activating the TiO_2-coated fibres for pollutant breakdown. To enhance the efficiency of the UVC light, a reflective sheet is integrated around the brushes within the casing (Figure 6). This high-efficiency reflective material maximises the distribution of UV light across the fibres, ensuring that the entire surface area is exposed to the germicidal and photocatalytic effects.

- PCO filter: This stage involves a PCO filter integrated within the UVC light chamber. Air passes through a circular array of organic brushes resembling a mop, coated with TiO_2. When illuminated by UVC light, the TiO_2 acts as a photocatalyst, generating ROS that oxidises and decomposes VOCs and other chemical pollutants (Figure 7).
- Bio-aerogel filter: Positioned downstream of the whole system is the innovative bio-aerogel filter, a key component developed specifically for this prototype. The bio-aerogel material is an ultra-lightweight, highly porous material derived from sustainable biomass, developed by the Hubei University of Technology for sustainability and performance. The bio-aerogel samples were prepared in circles of 130 mm of diameter and 10 mm thickness (Figure 8).

Figure 4. H13 HEPA filter
Abbreviation: HEPA: High-Efficiency Particulate Air.

Figure 6. Light pipe

Figure 5. 20W UVC light bulb

Figure 7. PCO "Mop" filter
Abbreviation: PCO: Photocatalytic oxidation.

Figure 8. Bio-aerogel sample fabricated

Figure 9. MopFan pre-commercial prototype developed for testing

The bio-aerogel's multi-layered micro- and nano-scale pores maximise surface area, enhancing its ability to retain viral particles and sustain contact with the antimicrobial salt coating, ensuring effective antiviral action. For this study, the bio-aerogel was impregnated with NaCl, which is known for its antiviral properties, particularly in creating a hypertonic environment that destabilises viral particles upon contact. This salt was sourced from high-purity commercial suppliers (Fisher Scientific) to ensure the absence of contaminants that might affect experimental outcomes. The salt solution was prepared in deionised water at concentration 20% as described by Wang *et al.*[28] The bio-aerogel remains stable across varied temperature and humidity conditions, making it suitable for real-world use.

Positioned at the final stage, the bio-aerogel filter complements the HEPA filtration, TiO_2-coated fibres, and UVC irradiation, ensuring comprehensive contaminant removal. This multi-stage approach improves IAQ efficiently and sustainably.

2.2. Device characteristics

The MopFan stands at a height of 640 mm, with a width and depth of 300 mm each, giving it a compact and well-proportioned form suitable for various indoor settings. The device weighs approximately 4.5 kg, making it lightweight and easy to relocate as needed. Its housing was 3D-printed from environmentally friendly polylactic acid + with a silk finish (Figure 9).

The air purification system is powered by a variable-speed fan that provides three distinct airflow settings. At low speed, the fan delivers an airflow rate of approximately 85 m^3/h, ideal for quieter operation in small spaces. The medium speed setting offers an airflow of about 100 m^3/h, balancing performance and noise, while the high speed reaches 185 m^3/h, suitable for rapid purification needs.

Powering the MopFan is powered by a standard main power supply of 220 – 240 V AC at 50 Hz. The device has a maximum power consumption of 50 W when operating at the highest fan speed.

3. Testing setup

3.1. Measurement instruments

For accurate and reliable air quality evaluation of the MopFan, two primary instruments were used: the Temtop M2000 2^{nd} CO_2 Air Quality Monitor and the Temtop LKC-1000S+ 2^{nd} Air Quality Monitor. The Temtop M2000 measured particulate matter ($PM_{2.5}$ and PM_{10}), carbon dioxide (CO_2), HCHO, temperature, and humidity. The Temtop LKC-1000S+ provided a broader range of measurements, including $PM_{2.5}$, PM_{10}, HCHO, total VOCs (TVOCs), air quality index, particle count, temperature, and humidity (Figure 10).

3.2. Source of pollutants

Ethanol was chosen as the test contaminant for its suitability as a surrogate for VOCs and HCHO, both of which are common indoor pollutants with notable health risks. Ethanol has been widely employed as a source for VOCs and HCHO in photochemical studies (e.g., Jia *et al.*[29]). Its high vapour pressure at room temperature (approximately 5.8 kPa at 20°C) allows for rapid evaporation and uniform dispersion, effectively mimicking the behaviour of many VOCs. Ethanol's low-molecular-weight and high volatility contribute to rapid atmospheric diffusion and a heightened reactivity with hydroxyl radicals, which tend to favour faster oxidation processes. Atkinson and Arey[30] reported that ethanol undergoes effective photolysis when irradiated at wavelengths shorter than approximately 220 nm. In addition, ethanol can be accurately detected using standard instruments such as air quality monitors and flame ionisation detectors, ensuring precise measurement of concentration changes during experiments. In contrast, many other sources of VOCs, such as aromatic hydrocarbons, often display slower reaction kinetics and different secondary pollutant formation pathways. Future studies will be directed toward examining a broader range of VOCs.

3.3. Test environment

The experimental assessments were conducted in three distinct rooms located in separate residential houses, representing typical indoor environments. The selected rooms varied in size and function: a small office/study room, a medium-sized bedroom, and a large living room. Each room featured only one entrance door and one window, simplifying the ventilation dynamics and allowing for controlled manipulation of environmental variables.

3.3.1. Small room (office/study)

The small room used in this study was an L-shaped space with an area of approximately 4.26 m^2, consisting of a main section (1.8 m by 1.9 m) and an extension (1 m by 0.9 m).

Figure 10. Sensors used. (A) Sensor placed downstream: Temtop M2000; (B) Sensor placed upstream: Temtop LKC-1000S.

Furnishings were minimal to promote good air circulation, including a desk with a chair, a table under the window, and a small bookshelf. The entrance door was on the west wall, while the window on the east wall provided natural light and ventilation (Figure 11).

3.3.2. Medium room (bedroom)

The medium room was a rectangular bedroom with dimensions of 2.8 m by 2.7 m, giving a total area of 7.56 m^2. It was furnished with a single-sized bed against the east wall, a bedside table, an ottoman, and a small desk near the window. The entrance door was on the south wall, opening inward, while a window on the east wall provided natural light and ventilation (Figure 12).

3.3.3. Large room (living room)

The large room used in this study was a living room with a total area of approximately 14.07 m^2, measuring 2.76 m in width by 4.8 m in length. The room was furnished as a typical living space, featuring a sofa set in the main section, a coffee table, an entertainment centre against the west wall, and a couch in the left corner. The layout included an entrance door on the east wall, opening inward, and a large window on the north wall (Figure 13).

3.4. Variables and parameters

A structured experimental framework was employed to assess the performance of the air purification device under various environmental conditions. The variables were carefully categorised into independent, dependent, and controlled variables to facilitate systematic analysis.

3.4.1. Independent variables

The independent variables manipulated during the experiments were as follows:

- **Room size**: To evaluate the purifier's efficiency relative to spatial volume, three room sizes representative of typical residential spaces were selected:

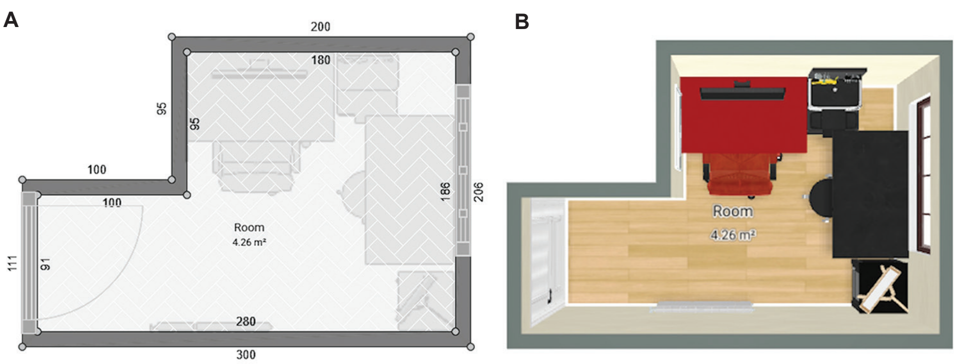

Figure 11. Small room. (A) Floor plan; and (B) 3D Top view.

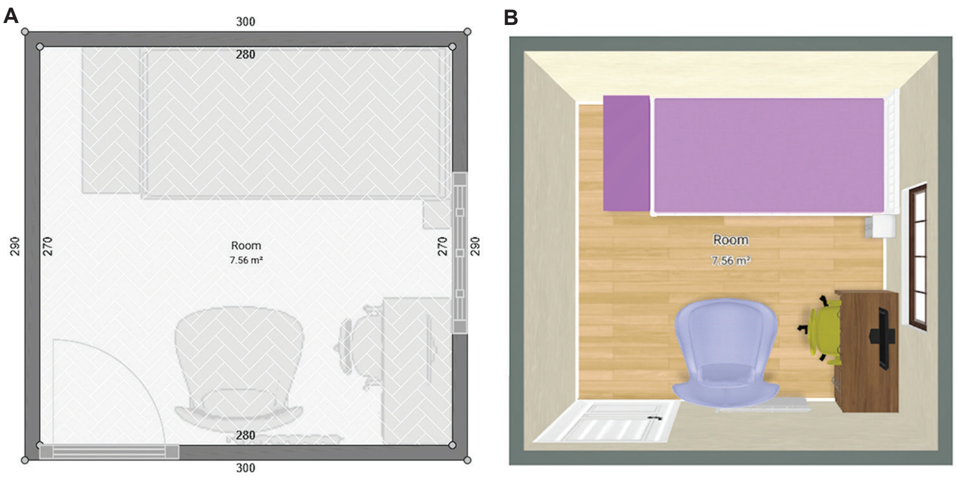

Figure 12. Medium room. (A) Floor plan; and (B) 3D Top view.

Figure 13. Large room. (A) Floor plan; (B) 3D Top view; and (C) Picture of the MopFan.

  - Small room;
  - Medium room;
  - Large room.
- Purifier speed settings: The device was operated at three different fan speeds to determine the impact of airflow rate on contaminant removal:
  - Low speed;
  - Medium speed;
  - High speed.
- State of door and window: Ventilation conditions were altered by adjusting the state of the door and window, simulating different environmental scenarios:
  - Closed: Both door and window closed, creating a non-ventilated environment;
  - Open: Door and/or window open, introducing natural ventilation.

3.4.2. Dependent variable

The primary dependent variable measured was:

- Pollutant concentration over time: The concentration of pollutant vapours was continuously monitored throughout each test to evaluate the rate of reduction attributable to the air purifier under varying conditions.

3.4.3. Controlled variables

To ensure consistency and reliability of the results, the following variables were kept constant across all experiments:

- Initial pollutant volume: A precise volume of 1 mL of ethanol was evapourated at the start of each test to maintain a uniform initial contaminant level;
- Duration of tests: Each experiment was conducted over a fixed period of 3 h, providing sufficient time to observe significant changes in ethanol concentration;
- Position of purifier: The air purifier was consistently placed 1 metre away from the ethanol source in all tests to eliminate positional variability and ensure consistent airflow patterns.

3.5. Experimental matrix

The experimental matrix was designed to systematically evaluate the air purification device under different conditions, including variations in room size (Table 1), purifier speed settings (Table 2), and door/window states (Table 3). Tests were conducted in a randomised order to reduce biases from environmental fluctuations or equipment inconsistencies, enhancing the reliability of results. The matrix explored three main effects: the impact of room size on purifier efficiency with constant closed-window ventilation, the influence of purifier fan speed across different room sizes, and the effect of natural ventilation by comparing results with windows open and closed at different purifier speeds in the small room.

4. Testing procedures

As shown in Figure 14, to prepare the test environments, the MopFan was placed centrally within each room to ensure optimal air circulation and uniform exposure to airborne contaminants. An electric hotplate, preheated to the boiling point of ethanol (78.3°C), was positioned 1 metre away from the purifier. This setup facilitated the controlled evaporation of a precise volume of ethanol into the environment, simulating elevated levels of VOCs.

The two air quality sensors were strategically placed to monitor ethanol concentrations. One sensor was positioned upstream of the purifier to measure the ambient ethanol levels entering the device, while the other was placed downstream to assess the concentration of ethanol in the air after purification. This arrangement enabled the precise evaluation of the purifier's efficacy in reducing ethanol vapours. Both air quality monitors were configured to record one reading per minute throughout each experiment.

A timer was set for a duration of 2 h to standardise the testing period across all experiments. At the start of each experiment, the ethanol (1 mL) was introduced onto the preheated hotplate, and the MopFan was activated at the designated fan speed setting (low, medium, or high). Environmental conditions such as temperature and humidity were recorded to ensure consistency and control throughout the experimental process.

Table 1. Effect of room size experimental matrix

Room size	Purifier speed	Ventilation state
Small	Low	Closed
Medium	Low	Closed
Large	Low	Closed
Small	Medium	Closed
Medium	Medium	Closed
Large	Medium	Closed
Small	High	Closed
Medium	High	Closed
Large	High	Closed

Table 2. Effect of purifier speed experimental matrix

Room size	Purifier speed	Ventilation state
Small	Low	Closed
Small	Medium	Closed
Small	High	Closed
Medium	Low	Closed
Medium	Medium	Closed
Medium	High	Closed
Large	Low	Closed
Large	Medium	Closed
Large	High	Closed

Table 3. Effect of ventilation state experimental matrix

Room size	Purifier speed	Ventilation state
Small	Low	Closed
Small	Low	Open
Small	Medium	Closed
Small	Medium	Open
Small	High	Closed
Small	High	Open

For our control experiments designed to evaluate the effect of room size, the same amount of ethanol was introduced and the identical procedure was followed as in the experimental tests, except that the MopFan was not operating.

5. Results

In the following sections, we describe and interpret the observed trends in pollutant degradation, with particular reference to HCHO and TVOC measurements.

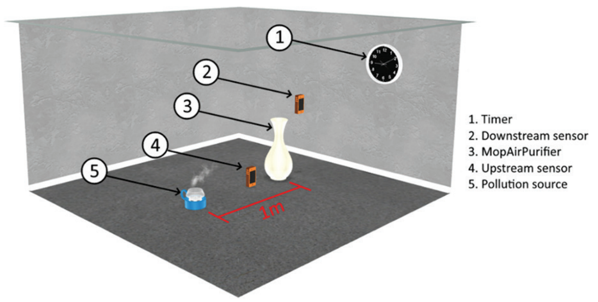

Figure 14. Diagram of the testing setup

5.1. Room size effect

Figures 15 and 16 compare the degradation kinetics of HCHO and TVOCs, respectively, across three different room sizes – small, medium, and large – while maintaining identical initial pollutant loads and test procedures. The graphs display the downstream concentration of HCHO and TVOCs as a function of time. As expected, the larger rooms, with their higher air volumes, show lower initial and throughout pollutant concentrations due to dilution effects.

However, it is important to consider both the absolute and relative changes. Although the absolute concentrations in larger rooms are lower at all times compared to the small room, the active operation of the MopFan produces a marked improvement over the corresponding control tests (where the device was inactive). In some parts of the control data, the pollutant concentration curve appears truncated. This is due to sensor saturation. In the small room, the higher initial concentration (due to a smaller air volume) leads to a more pronounced reduction on activation of the device, highlighting the efficiency of the recirculation process in confined spaces. Conversely, in the larger rooms, while the overall concentration is lower from the start due to dilution, the purification effect is still evident when compared to control measurements, indicating that the MopFan effectively further reduces pollutant levels even in environments with lower baseline concentrations.

5.2. Purifier speed effect

Figures 17 and 18 illustrate the effect of different fan speeds (low, medium, and high) on the removal rates of HCHO and TVOCs, respectively, in a fixed room size. The graphs plot the removal efficiency over time under varying air flow conditions. It is important to note that the data in these figures are a rearrangement of our earlier results, intended to provide a different perspective by focusing on the integrated system performance rather than on the isolated reaction kinetics.

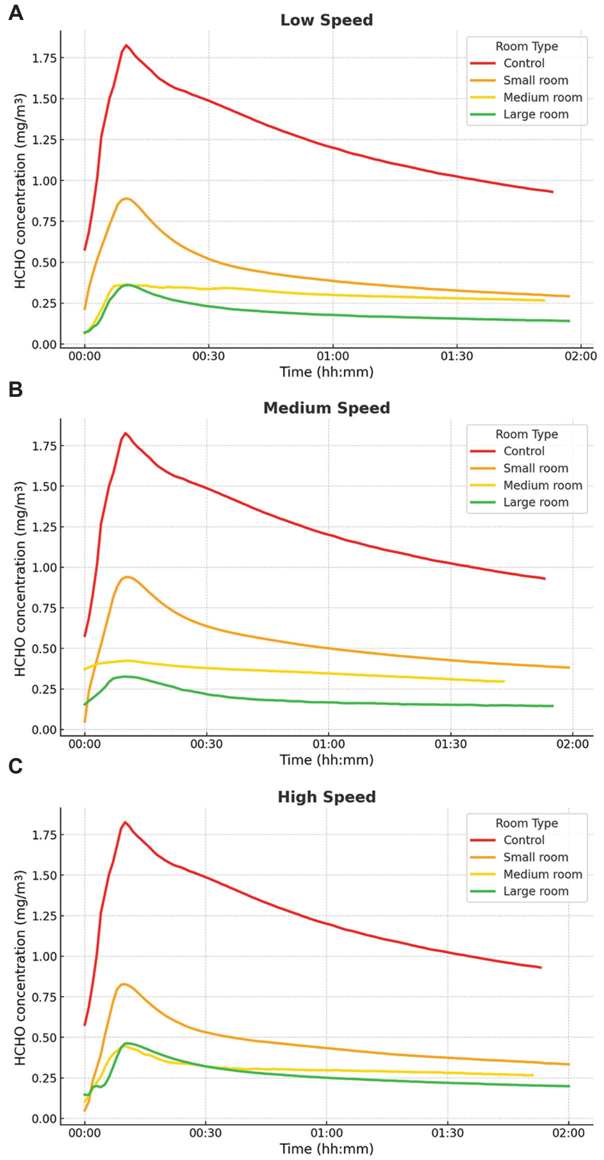

Figure 15. Comparison of formaldehyde (HCHO) concentration over time in various room sizes (small room, medium room, and large room) at different airspeeds: (A) Low, (B) medium, and (C) high

Although it might be anticipated that a higher fan speed would enhance air recirculation and thereby improve purification efficiency, our experimental data indicate that the downstream concentrations of both VOCs and HCHO do not vary significantly across the range of fan speeds tested. In the case of the MopFan, the differences between the low-, medium-, and high-speed settings are relatively modest. Consequently, the rapid nature of the photolytic and photocatalytic reactions appears to render the slight variations in air turnover inconsequential with respect to overall pollutant removal.

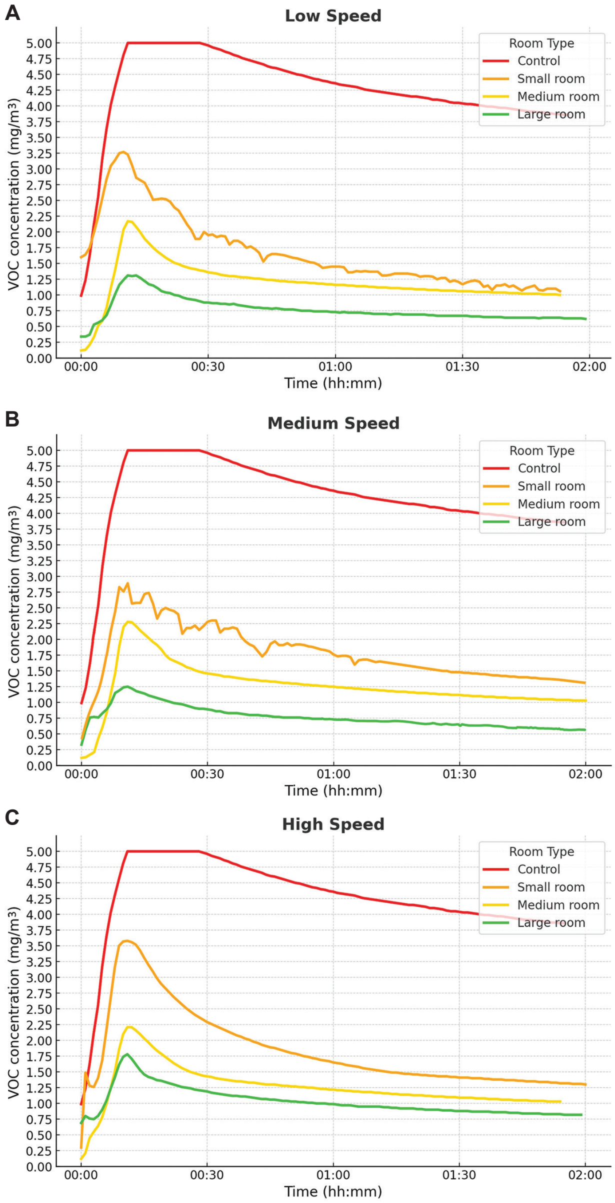

Figure 16. Comparison of volatile organic compound concentration over time in various room sizes (small room, medium room, and large room) at different airspeeds: (A) Low, (B) medium, and (C) high

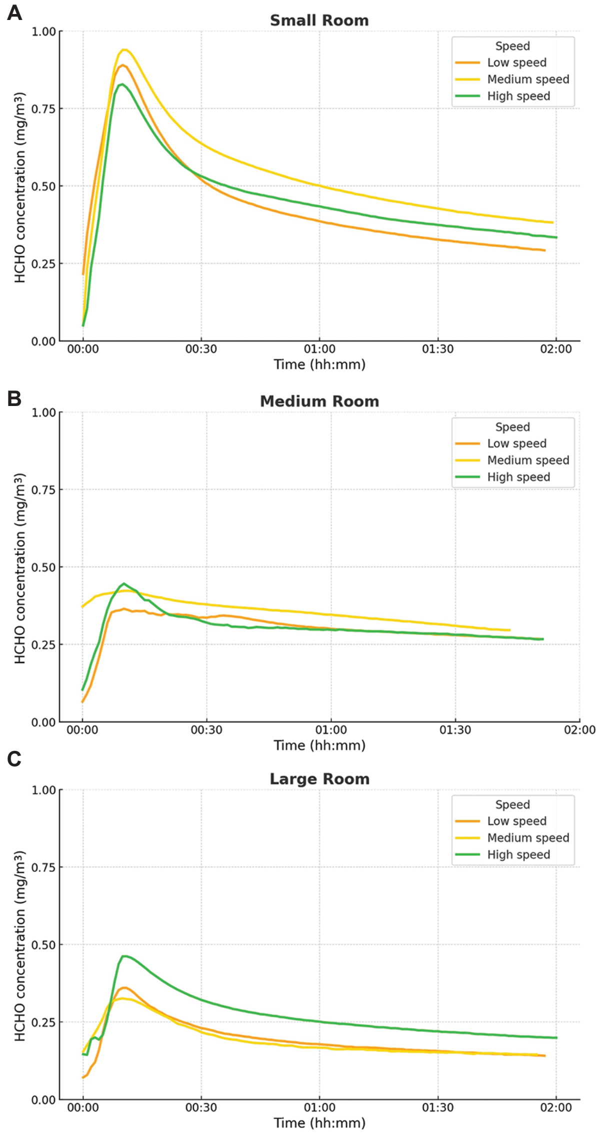

Figure 17. Comparison of formaldehyde (HCHO) concentration over time at various airspeeds (low speed, medium speed, high speed) at different room sizes: (A) Small room, (B) medium room, and (C) large room

5.3. Ventilation state

In Figures 19 and 20, the effect of the ventilation state on pollutant removal is illustrated. Figure 19 presents the temporal profiles of HCHO concentrations measured downstream under two different ventilation conditions – closed versus open – at low, medium, and high fan speeds. It shows that when the ventilation is open, there is a marked dilution effect, resulting in lower HCHO levels over time compared to the closed environment, where pollutant levels remain elevated due to the absence of fresh air exchange. Similarly, Figure 20 depicts the TVOC concentration trends under the same conditions, again demonstrating that open ventilation consistently leads to lower pollutant concentrations after the initial phase.

In each case, the open-ventilation line initially peaks higher – likely because the pollutant is introduced into a larger effective volume that quickly disperses the vapours – but subsequently drops to values below those observed with closed ventilation after roughly 15 – 30 min. By contrast, the closed-ventilation lines maintain higher concentrations over time, as there is no influx of external air to dilute the contaminant load, even though the MopFan is actively

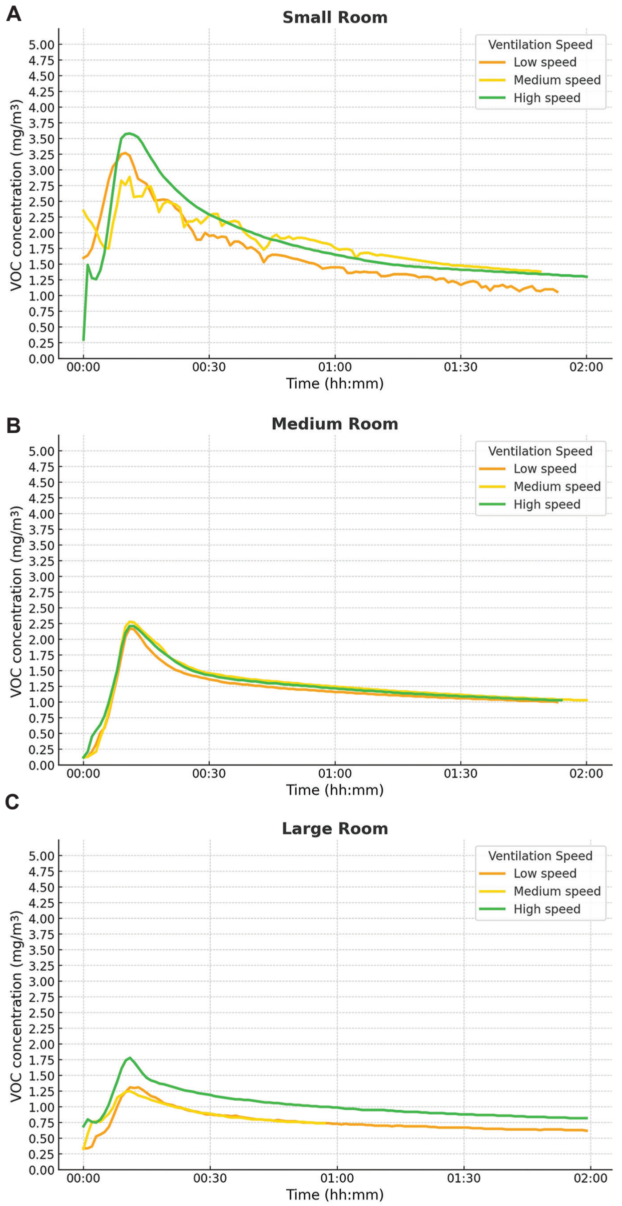

Figure 18. Comparison of volatile organic compound concentration over time at various airspeeds (low speed, medium speed, sigh speed) at different room sizes: (A) Small room, (B) medium room, and (C) large room

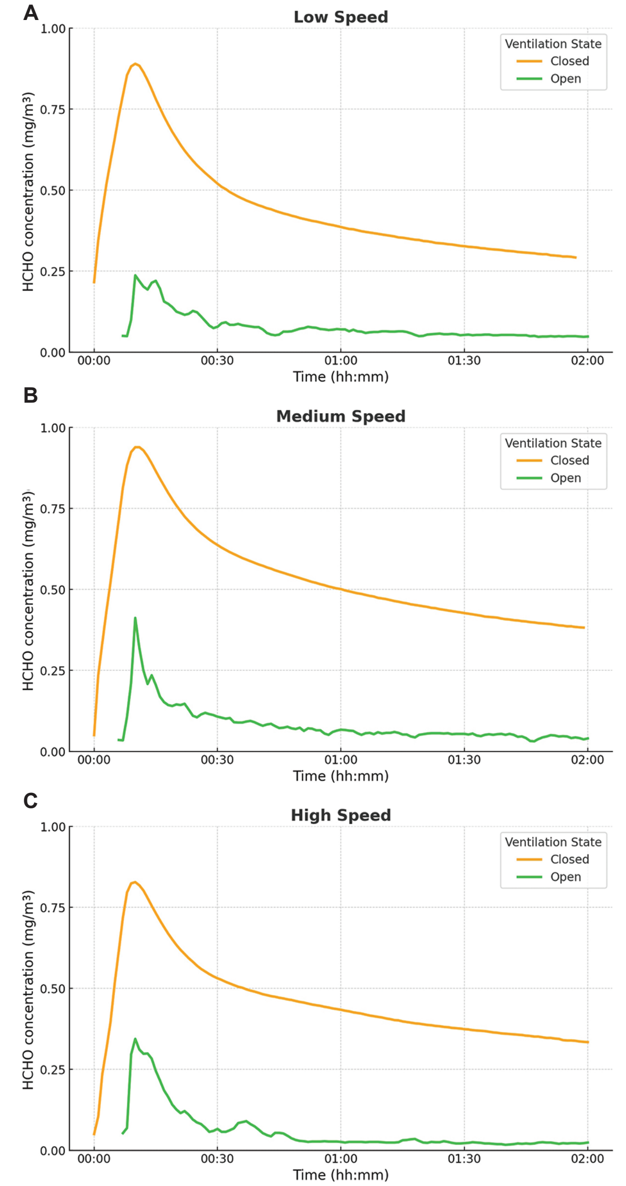

Figure 19. Comparison of formaldehyde (HCHO) concentration over time of two ventilation states (closed vs. open) at different airspeeds: (A) Low, (B) medium, and (C) high

purifying the recirculated air. Interestingly, this pattern is evident across all three fan speeds, indicating that even modest external airflow substantially lowers the pollutant levels once the initial spike has subsided.

6. Discussion

The experimental findings demonstrate that the MopFan's performance in reducing HCHO concentrations is markedly influenced by a range of environmental factors and operational settings. In particular, the device exhibited variable efficacy depending on room volume and ventilation conditions, reflecting the complex interplay between air circulation dynamics and pollutant degradation rates.

6.1. Effect of room size

Room volume proved to be a significant determinant of purification efficiency, with larger spaces exhibiting less reduction in pollutant concentration as compared to smaller rooms. This effect can be attributed to the increased air volume and potentially lower circulation rates in more

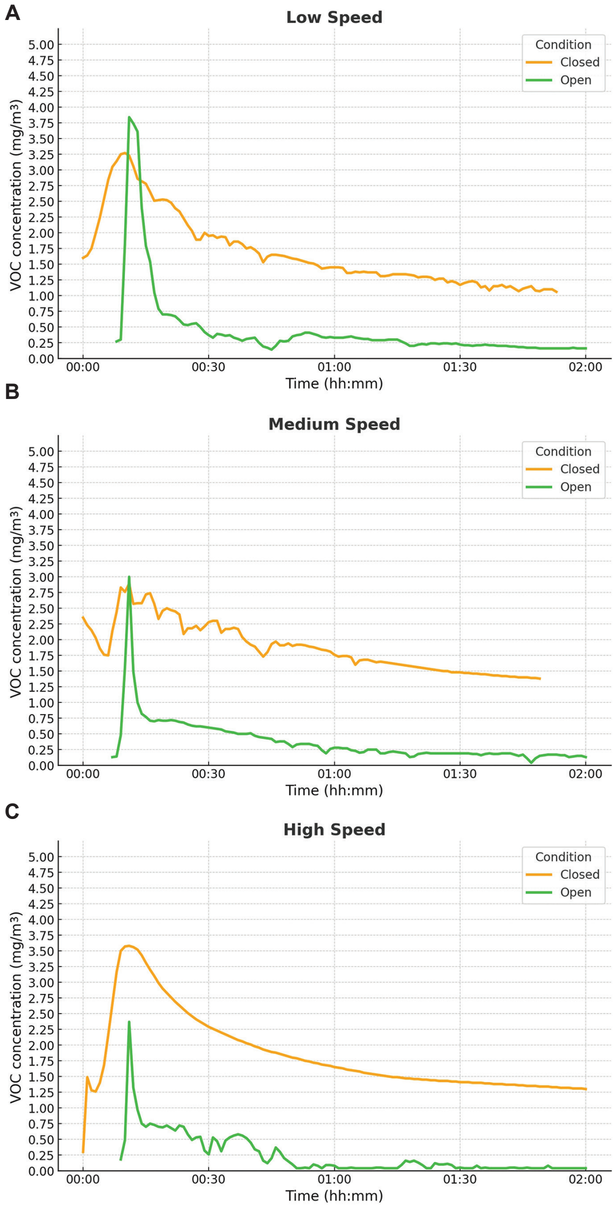

Figure 20. Comparison of volatile organic compound concentration over time of two ventilation states (closed vs. open) at different airspeeds: (A) Low, (B) medium, and (C) high

expansive areas, which may dilute the concentration of VOCs relative to the purifier's intake capacity. In smaller rooms, the device's intake appears to capture a higher proportion of the room's air volume per unit time, facilitating a faster and more uniform reduction in VOC concentrations. The findings align with the theoretical expectations for air purification in constrained versus expansive environments, suggesting that higher-capacity or multiple units may be required for effective treatment in larger residential spaces.

6.2. Effect of purifier speed

The impact of fan speed on the purifier's performance in removing VOCs, specifically ethanol, reveals a modest relationship between airflow rate and purification efficacy. Our results indicate that, within the operational range of the MopFan, the differences between low, medium, and high speeds are minimal, suggesting that modest variations in airflow do not significantly alter the net purification outcome. These findings underscore that while air recirculation is a necessary component of the purification process, the rate of chemical degradation is sufficiently rapid that the modest differences in fan speed do not translate into measurable differences in performance. Further studies employing a wider range of speeds or different system configurations may be required to determine whether a broader spectrum of airflows would impact the purification efficiency.

It is important to note that the intrinsic mechanisms of each purification stage – namely the HEPA filter, the UVC irradiation, the PCO process, and the bio-aerogel antiviral filter – operate essentially instantaneously on contact with the contaminated air.

6.3. Effect of ventilation (windows and door open/closed)

Natural ventilation, introduced by opening windows and doors, significantly influenced the purifier's performance. This observation can be attributed to the dilution effect introduced by external fresh airflow, which likely disperses contaminants throughout the room, diminishing the purifier's ability to achieve rapid reductions in TVOC and HCHO concentrations. When windows were closed, the controlled environment allowed the purifier to operate effectively by recirculating and treating a more stable air volume.

6.4. Operational recommendations

Each filtration stage contributes uniquely to the MopFan's overall air purification performance. For environments requiring high pathogen deactivation, operating the device at higher speeds with closed windows optimises exposure to UVC and PCO processes, while the bio-aerogel filter enhances viral deactivation even further. High-speed settings are recommended primarily for particulate removal and rapid VOC reduction in smaller spaces. Thus, within the operational range of the MopFan, variations in fan speed do not alter the fundamental reaction kinetics of these processes. Instead, increasing the airflow rate results in a higher volume of air being circulated through the device per unit time, which enhances the overall removal of contaminants.

6.5. Assessment of ethanol removal efficiency

The device's ability to reduce ethanol vapours, utilised as a representative VOC and HCHO, was systematically demonstrated and analysed across different conditions. Ethanol concentration reductions were consistently observed, though the efficacy varied in direct response to the operational settings discussed above. High fan speed in smaller, closed rooms yielded the most substantial ethanol reduction rates, while large, ventilated spaces showed the least pronounced results. These findings suggest that ethanol, due to its high volatility, requires continuous air intake and circulation to ensure effective removal, thus reinforcing the significance of optimised operational parameters.

The evaluation was performed over the small room set of tests, using mathematical integration to compute the area under the curve (AUC) of pollutant concentrations over time. The AUC provides a cumulative representation of pollutant levels, enabling the comparison of the purification device's performance against the baseline (control test).

The trapezoidal rule was selected as the integration method due to its appropriateness for the smooth and discretised nature of the experimental data:

$$AUC = \int_{t_0}^{t_n} C(t)\,dt \approx \sum_{i=1}^{n-1} \frac{C(t_i) + C(t_{i+1})}{2} \cdot (t_{i+1} - t_i)$$

Where $C(t)$ is the concentration at time t; and t_i and t_{i+1} are consecutive time points.

Then, the purification efficiency was expressed as a percentage reduction relative to the control test, calculated as follows:

$$Reduction\% = \left(\frac{AUC_{Control} - AUC_{Test}}{AUC_{Control}} \right) \times 100$$

This metric quantifies the relative improvement in air quality achieved by the device compared to the baseline condition. The results are summarised in Table 4.

Our statistical analysis, based on triplicate measurements for each fan speed condition under closed ventilation, confirms the robustness of MopFan's performance. The mean TVOC removal efficiencies ranged between 55.2% and 59.2%, while HCHO removal efficiencies were between 61.5% and 65.1%, with moderate standard errors. A one-way analysis of variance yielded p=0.17 for VOCs and 0.20 for HCHO, indicating that the differences observed across different fan speeds are not statistically significant (p>0.05).

It is worth noting that the differences reported in Table 4 are relatively modest and generally fall within the standard error ranges. While wind speed intensity may conceptually affect ventilation and pollutant dilution, in our experiments, statistical analysis indicates that these variations across fan speeds may not be significant. Thus, while the data suggest that low-speed settings can achieve a marginally higher pollutant reduction in a small room, the practical impact on IAQ is minimal.

The divergence between the reduction of TVOCs and that of HCHO could plausibly indicate that certain VOCs have lower photolysis efficiency under 185 nm irradiation compared to HCHO, potentially due to differences in their absorption cross sections or quantum yields. However, it is also important to consider that the overall removal performance in our system is a function of both photolytic reactions and the multi-stage filtration processes employed. Further kinetic studies on individual VOC species would be necessary to conclusively determine whether some are less susceptible to photolysis at 185 nm.

6.6. Limitations of the study

While this study provides valuable insights into the operational dynamics of the MopFan, several limitations must be acknowledged:

- Potential sources of error: Variability in environmental factors, such as minor fluctuations at ambient temperature and humidity, could influence VOC concentration measurements.
- Constraints due to equipment or environmental factors: The study was conducted in three specific room sizes,

Table 4. Pollutant removal efficiencies in small room

Test	Pollutant	Control AUC	Test AUC	Reduction (%)	Standard error (%)
Small room – low speed	TVOC	495.92	202.01	59.26	±3.2
Small room – medium speed		495.92	221.1	55.41	±3.0
Small room – high speed		495.92	222.12	55.21	±3.1
Small room – low speed	HCHO	181.23	63.12	65.17	±2.9
Small room – medium speed		181.23	69.87	61.44	±3.3
Small room – high speed		181.23	69.68	61.54	±3.0

Abbreviations: AUC: Area under the curve; HCHO: Formaldehyde; TVOC: Total volatile organic compounds.

each with a unique layout and ventilation arrangement. These configurations, while representative, may not encompass the full range of possible residential settings, potentially limiting the generalisability of the results. Furthermore, the reliance on ethanol as a surrogate for VOCs, while justified by its physical properties, may not perfectly represent the purifier's efficacy against other chemically distinct indoor pollutants.

- Long-term durability: The present study did not incorporate extended operational testing or a detailed economic analysis. Based on available supplier specifications and literature, the HEPA filter is recommended for replacement every 6 – 8 months under standard operating conditions. The UVC lamp is rated for approximately 9,000 h of continuous operation, which may correspond to over 1 year of typical intermittent use. Tampico fibres, serving as the substrate for the TiO_2 coating, are expected to retain their structural integrity for 1 – 2 years under moderate indoor conditions, though continuous exposure to UV radiation and pollutant loads might accelerate their degradation. In the case of the bio-aerogel filter, long-term durability studies are still pending; preliminary assessments suggest that its efficiency is maintained for at least 2 months of continuous operation. These provisional estimates provide a preliminary framework for evaluating maintenance schedules and overall cost-effectiveness, but further long-term testing is required to validate these projections and fully assess the device's economic viability.

Overall, these limitations suggest areas for future research, including broader testing in varied residential configurations and with a wider array of VOCs, to more comprehensively evaluate the MopFan's versatility and performance in real-world applications.

6.7. Evaluation of overall purification effectiveness

The MopFan employs a multi-stage filtration process, each component contributing uniquely to the device's overall air purification capacity. This section examines the individual characteristics and purification efficiencies of each stage, assessing their contributions to particulate removal, pathogen inactivation, and VOC degradation.

6.7.1. Stage 1: HEPA filter

The initial filtration stage uses a HEPA filter rated H13 classification under BS EN 1822 – 1:2019, captures 99.95% of particles ≥0.3 μm. This filter consistently achieves PM_{10} and $PM_{2.5}$ particle reduction efficiencies ranging from 92% to 98%.[31]

6.7.2. Stage 2: UVGI

The 185 nm UVC lamp targets microorganisms, disrupting nucleic acids in viruses and bacteria. Based on literature, we can expect around 85 – 90% viral reduction. This effectiveness assumes optimal conditions, such as low or medium fan speeds, which allow sufficient exposure time for UVC irradiation to disrupt viral RNA and DNA.[32]

6.7.3. Stage 3: PCO filter

The PCO stage leverages TiO_2-coated surfaces activated by the UVC light to generate ROS, decomposing VOCs. Data from testing showed that, in spaces with low ventilation, the PCO filter achieved VOC reduction rates of up to 59% at low speed, while the HCHO degradation was closer to 65%.

6.7.4. Stage 4: coated bio-aerogel filter

The bio-aerogel filter is designed to adsorb residual contaminants and inactivate pathogens, specifically with salt and TiO_2 coatings. According to Coleman *et al.*'s results,[33] this filter demonstrated notable antiviral efficacy, achieving a ≥1-log reduction in viral titre within the first 10 min of contact. In other words, when air flows through this filter, about 90% of viruses are inactivated within the first 10 min. With extended contact, such as in enclosed spaces with low airflow, nearly 100% inactivation (no detectable virus) was achieved within 60 min.[33]

6.8. Comparison with a commercial device

To preliminary benchmark the MopFan's performance, we compared it directly with a commercially available TruSens Z-1000 air purifier under the same test conditions (Figure 21). The TruSens Z-1,000, designed for spaces up to 23 m^2, employs a similar HEPA filtration system combined with activated carbon, plus a UV light. It

Figure 21. Commercially available air purifier *TruSens Z-1000*

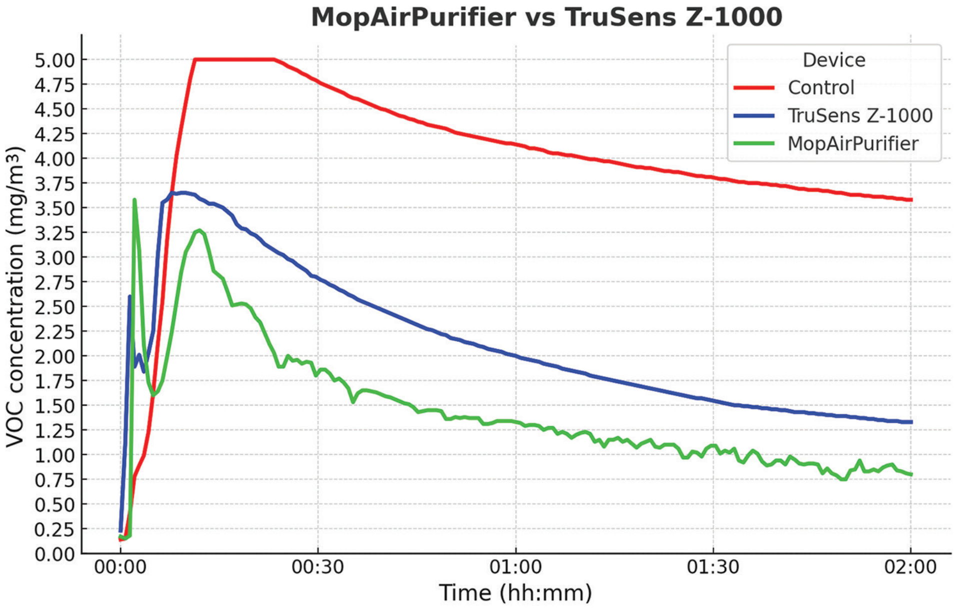

Figure 22. Comparison between MopFan and TruSens Z-1000 of volatile organic compound concentration over time in a closed small room at high speed

typically retails for approximately £120 in the UK market. In contrast, the MopFan prototype integrates a multi-stage approach, including a HEPA filter, UVC lamp (for photocatalytic activation), and a bio-aerogel filter for antiviral and chemical filtration. The cost of the prototype was approximately £200.

In Figure 22, which tracks VOC concentrations over 2 h, the MopFan achieves lower pollutant levels than the TruSens at nearly every time point, while the control shows only a slow natural decay. Specifically, after 30 min, the MopFan reduced VOC concentrations by about 60%, compared to 45% with the TruSens. By the 2-h mark, the MopFan stabilised around 1.5 mg/m^3, whereas the TruSens hovered closer to 2.0 mg/m^3, suggesting that the MopFan's additional photocatalytic stage may confer enhanced chemical degradation capabilities.

A similar trend is observed in Figure 23, which plots HCHO concentrations under the same experimental protocol. Once again, the MopFan demonstrates a more pronounced reduction in HCHO compared to the TruSens. After the initial peak, the MopFan's HCHO levels dropped below 0.5 mg/m^3 by around 30 min, whereas the TruSens remained near 0.75 mg/m^3, and the control stayed above 1.0 mg/m^3. This result further supports the hypothesis that the MopFan's multi-stage filtration system effectively degrades gaseous pollutants in addition to capturing particulates.

In terms of cost and energy consumption, the TruSens Z-1000's power draw (≈40 W) is slightly lower than the MopFan's maximum of 50 W. However, both devices fall

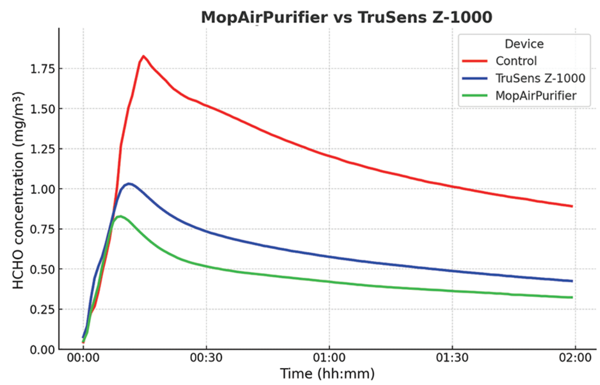

Figure 23. Comparison between MopFan and TruSens Z-1000 of formaldehyde (HCHO) concentration over time in a closed small room at high speed

within a comparable range of power consumption, and the MopFan's prototype cost is expected to be competitive on scaling. Thus, while the TruSens is a robust commercial product, the MopFan demonstrates superior removal of VOCs and HCHO, likely due to the synergistic action of its multiple filtration stages. Additional market comparisons, including noise levels and filter replacement intervals, would further clarify the MopFan's positioning among existing air purifiers, but these preliminary findings indicate that the MopFan performs strongly against a leading commercial unit.

7. Conclusion

This study evaluated the MopFan air purification device, integrating advanced technologies such as PCO, and bio-aerogel filtration, under controlled experimental conditions to address the challenges of indoor air pollution. The findings confirm its efficacy in reducing indoor air pollutants, particularly VOCs and HCHO, under various environmental conditions. The following conclusions can be drawn:

7.1. Air purification efficacy

The MopFan demonstrated its highest efficiency in smaller, enclosed spaces, achieving up to 65% reduction in HCHO concentrations at low fan speeds. In larger spaces, purification rates were diminished due to the increased air volume and reduced circulation efficiency.

The device was less effective under natural ventilation conditions due to pollutant dilution, emphasising its optimal performance in closed environments where air is consistently recirculated through the filtration system.

7.2. Operational parameters and optimisation

The experimental results demonstrate that the MopFan's performance is robust across a range of operational conditions, and its efficacy is influenced by room size, fan speed, and ventilation state. In smaller, enclosed spaces, the limited air volume promotes frequent recirculation, which, in turn, enhances the removal of VOCs and HCHO. Although our analysis in the small room (closed ventilation) showed no statistically significant differences across low, medium, and high fan speeds ($p>0.05$), the rapid nature of the photocatalytic reaction in the MopFan ensures that modest variations in airflow do not compromise overall efficiency.

The MopFan's robustness – demonstrated by its consistent performance across different room sizes and fan speeds – underscores its practical applicability.

7.3. Technological implications of the MopFan design

The MopFan's modular design and incorporation of sustainable materials such as Tampico fibres and bio-aerogels highlight the potential for scalable, eco-friendly air purification solutions.

The integration of UVC light with reflective materials maximised photocatalytic activation, enhancing pollutant degradation efficiency while mitigating secondary pollutant formation, a common challenge in PCO-based systems. The innovative multi-stage filtration approach, particularly the integration of TiO_2-coated fibres and bio-aerogel filters, effectively addressed a range of pollutants. The bio-aerogel's high porosity and antiviral properties provide added value, especially for pathogen inactivation.

7.4. Future research and development

7.4.1. Expanded testing environments

Further evaluations in varied residential and commercial settings with complex ventilation dynamics will improve the generalisability of findings and inform design modifications for diverse applications.

7.4.2. Broader pollutant spectrum

Future studies should explore the MopFan's performance against a wider range of VOCs, microbial contaminants, and particulate matter to validate its comprehensive efficacy.

7.4.3. Integration into HVAC systems

Investigating the integration of MopFan technologies into existing HVAC (heating, ventilation, and air conditioning) systems could facilitate large-scale applications, particularly in densely populated or highly polluted urban areas.

7.4.4. Long-term durability and cost-effectiveness

Assessing the durability of components such as TiO_2-coated fibres and bio-aerogel filters under extended operation will determine maintenance requirements and lifecycle costs, which are critical factors for commercialisation.

7.4.5. Optimisation of photocatalytic systems

Continued refinement of PCO technology, focusing on minimising secondary pollutant formation and enhancing catalytic surface regeneration, will further improve its viability as a sustainable air purification solution.

This work contributes significantly to the growing body of knowledge on advanced air purification technologies, with the MopFan offering a promising, sustainable solution to mitigate indoor air pollution and enhance human health in diverse settings.

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Conflict of interest

Saffa Riffat is the Editor-in-Chief of the journal, but was not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. Separately, other authors declared that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data supporting the findings of this study are available from the corresponding author on reasonable request.

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